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RESEARCH MEMORANDUM

EFFECT OF IGNITOR DESIGN AND IGNITOR SPARK-GAP ENVIRONMENT ON IGNITION IN A TURBOJET COMBUSTOR

By Hampton H. Foster and David M. Straight

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

An investigation was conducted to determine the effect of ignitor design and ignitor spark-gap environment on the ignition-energy requirements of a single tubular turbojet-engine combustor. Data were obtained for a range of altitude inlet-air pressure at two air-flow rates and a range of combustor-inlet air and fuel temperature. Two fuels of different volatility were included in the investigation. The effects on ignition-energy requirements of (1) shielding the ignitor spark gap from high-velocity air flow, (2) fuel heating elements and auxiliary fuel feeds at the ignitor gap, and (3) gap width and ignitor spark-gap immersion depth were investigated with experimental ignitors of the air-gap type. The effect of electrode configuration, semiconductive materials in the spark gap, and spark-repetition rate were investigated with surface-discharge-type ignitors.

Shielding of the ignitor spark gap from high-velocity air flow and improvements in fuel-spray characteristics were effective means of improving ignition characteristics of the combustor; heating elements and auxiliary fuel feeds at the ignitor gap were ineffective. Over the range of conditions investigated, little difference in ignition limits was observed with several different designs of surface-discharge ignitors having either solid-ceramic semiconductors or glazed semiconductive coatings. Results with the triggered (glazed semiconductors) ignitors were generally superior to those with the nontriggered ignitors (solid-ceramic conductor) when fired by their respective ignition systems. The best of the surface-discharge ignitors gave better ignition performance than did a reference production-type air-gap ignitor using the same ignition supply system. However, elimination of the cooling-air flow in the reference ignitor resulted in ignition performance somewhat better than that of the best surface-discharge ignitor, each with its respective energy supply system.

Previously observed trends of better ignition characteristics with increased fuel volatility, increased inlet-air temperature, and increased spark-repetition rate were observed in this investigation.

INTRODUCTION

Ignition of turbojet engines at low temperatures and high altitudes presents a difficult problem for the engine designer. Improvements in weight and reliability factors of ignition systems are the goals of much intensive research. The investigation reported herein was conducted to study the effects of some of the ignition-system and ignitor-design factors on ignition characteristics of a turbojet-engine combustor.

Photographic studies in a full-scale transparent turbojet-engine combustor (ref. 1) have indicated that local liquid fuel-air mixtures around the ignitor spark gap varied considerably with combustor-inlet conditions and with fuel-spray characteristics. These studies and other research on ignition (refs. 2 to 5) have indicated that increased knowledge of the factors affecting ignition in turbojet-engine combustors, such as local air velocities and fuel-air mixtures around the ignitor spark gap and ignitor design and spark-system characteristics, is desirable in order to approach optimum ignition conditions and to minimize spark-energy requirements. Accordingly, an investigation was conducted at the NACA Lewis laboratory to determine the effect of the foregoing variables on the altitude-ignition limits of a single tubular turbojet-engine combustor. The research reported herein includes studies with both air-gap and surface-discharge types of ignitors. The air-gap ignitor-design studies included the effect on ignition characteristics of: (1) ignitor spark-gap electrode spacing, (2) spark-gap immersion in the combustor, (3) shielding the spark gap from high-velocity air flow, (4) fuel-heating elements at the spark gap, and (5) auxiliary fuel feeds at the spark gap. Surface-discharge ignitors were studied to investigate the effect on ignition characteristics of: (1) two semiconductive materials and (2) electrode configuration. The effects of the following variables on combustor ignition were also studied: (1) spark-repetition rate, (2) fuel-spray characteristics, (3) inlet-air temperature, and (4) fuel volatility.

The ignition systems used in this investigation were types that had previously been found to provide superior ignition characteristics; two were of commercial design (for firing either air-gap or surface-discharge ignitors), and one was of experimental laboratory design. All were of the low-voltage, high-energy variable-capacitance type.

Altitude-ignition data were obtained in the single combustor at two air-flow rates in the range of engine windmilling conditions, at a constant inlet-air and fuel temperature (10° F), and with a low-volatility (1-lb Reid vapor pressure) fuel. Limited data were also obtained with another fuel, MIL-F-5624A grade JP-4, for a range of inlet-air temperature. The data were analyzed to compare the relative merits of the ignitor designs and to evaluate the relative importance of the factors that affect ignition.

APPARATUS

Combustor Installation and Instrumentation

A single J33-A-23 turbojet-engine combustor (fig. 1) was installed in a direct-connect duct facility described in detail in reference 6. Air flow to the combustor was measured by a flat-plate orifice installed according to A.S.M.E. specifications. Instrumentation used for indicating combustor-inlet and -outlet air total pressures and temperatures is also described in reference 6. A copper fuel-cooling coil (50 ft long and 3/8 in. O.D.) was installed in the inlet-air duct close to the combustor to supply fuel at a temperature near that of the inlet air (fig. 1). The fuel-flow rate was indicated by a calibrated rotameter. A small (10.5 gal/hr 80° spray-cone angle) fixed-area fuel nozzle was used for most ignitor-design studies in order to maintain fuel atomization as nearly constant as possible. Starting fuel flows were between 25 and 50 pounds per hour for the air flows used; nozzle pressure drops were between 13 and 19 pounds per square inch. At these pressure drops, the fuel spray was well developed and was not significantly affected by air-flow currents in the combustor (ref. 1). A number of ignition tests were also conducted with a variable-area type and with a large fixed-area type fuel nozzle. The variable-area nozzle (ref. 7) afforded satisfactory spray characteristics over a wide range of fuel flow, whereas the spray characteristics of the large fixed-area nozzle (standard for the combustor used in this investigation) were poor at low fuel flows.

Ignition Systems

Three low-voltage, high-energy ignition systems were used in this investigation. All were of the capacitance type and are designated herein as experimental, triggered commercial, and nontriggered commercial systems. They are described in detail in the appendix.

Ignitors

The experimental ignitors investigated are listed in table I, together with some of the more important design features. Sectional and cutaway views of the electrode configurations of the ignitors are shown in figure 2. Photographs of the surface-discharge ignitors, together with two air-gap ignitors, are shown in figure 3.

The air-gap ignitors A through I were used to investigate the effects on combustor ignition characteristics of (1) shielding the spark gap from high-velocity air flow, (2) auxiliary fuel flow at the spark gap, and (3) fuel-heating elements at the spark gap. The effect of electrode

spacing on ignition was investigated with ignitor A and ignitor B, a modification of ignitor A. Ignitors K, L, and M are surface-discharge ignitors with solid-ceramic semiconductive material between the electrodes. Ignitors N through R were also of the surface-discharge type but with semiconductive coatings between the electrodes rather than solid ceramics. Ignitors O, P, and Q were of the same basic design; however, each had a different center electrode, which varied the electrode spacing and the depth of recess. Ignitor R is a slight modification of ignitor O in an attempt to nullify adverse effects of occasional fuel wetting experienced with ignitor O. Ignitor S (fig. 2(m)) was an air-gap ignitor with a geometry similar to that of several surface-discharge ignitors. The location of the ignitor spark gap in the combustor was essentially the same for all ignitors investigated unless specifically noted otherwise (fig. 4). The diametral clearance in the combustor of ignitors A through J was that of the standard configuration (1/16 in., fig. 4(a)) unless specifically noted otherwise. The corresponding clearance for ignitors K through S was essentially zero (fig. 4(b)). A hole in the ignitor body (outer shell) is provided in all ignitors for cooling-air entrance except as specifically noted (fig. 2). 3049

PROCEDURE

Fuels

The following two fuels were used in this investigation:

1. NACA fuel 50-197, a modified JP-3 fuel obtained by removing volatile components from MIL-F-5624A stock to adjust the Reid vapor pressure to a nominal 1 pound per square inch.

2. NACA fuel 52-288, MIL-F-5624A, grade JP-4.

An analysis of the two fuels is presented in table II. All tests were conducted with the first of these fuels unless specifically noted otherwise.

Test Procedure

Preliminary tests were conducted to determine the breakdown voltage of the nontriggered (solid-ceramic semiconductor) ignitors in the combustor with and without the fuel spray in operation over a range of combustor-inlet air density from 0.026 to 0.089 pound per cubic foot.

The minimum ignition-energy requirements of each experimental ignitor were determined as a function of combustor-inlet pressure. Data were obtained at two air-flow rates (1.87 and 3.75 lb/sec/sq ft) at a

constant inlet-air and fuel temperature of 10° F. Inasmuch as the experimental ignition system afforded a wide range of variable spark energy, the minimum ignition-energy requirements were determined for a range of combustor-inlet pressure from sea level to the ignition-limiting pressures of the combustor. With the commercial ignition systems, only five different values of spark energy were available; therefore, the limiting inlet pressure at which ignition could be obtained at each spark-energy level was determined with these systems. Data were also obtained with the best surface-discharge ignitor over a range of spark-repetition rate from 1/3 to 3 sparks per second and over a range of combustor-inlet air and fuel temperature from -40° to 140° F.

The following test procedure was used to determine the ignition limits of the combustor. The desired combustor-inlet air conditions were established, the ignition system was energized, and the desired spark-energy level was adjusted. Fuel was then admitted to the combustor by opening the throttle slowly until ignition occurred. A maximum time interval of about 30 seconds was allowed for ignition. The occurrence of ignition was indicated by a temperature rise in the combustor and also by visual observation of the flame through a large ($3\frac{1}{2}$ by 11 in.) window in the combustor. The criterion for satisfactory ignition was that the flame fill the combustor and continue burning after the ignition system was de-energized.

The energy of the three capacitance-type ignition systems was calculated as

$$E = 1/2\ CV^2$$

where

E energy, joules

C capacitance, farads

V voltage, volts

For comparison with ignition limits, the lowest combustor-inlet pressure at which steady-state burning could be maintained was determined from time to time during the ignition investigation. A detailed description of the test procedure is found in reference 2.

RESULTS AND DISCUSSION

The results of the investigation to determine the effect of several variables on the ignition-energy requirements of turbojet-engine combustors are presented and discussed in the following order: (1) air-gap ignitor design, (2) surface-discharge ignitor design, (3) ignition supply system, and (4) fuel-air mixture conditions.

Reproducibility of ignition data was not determined in the present investigation; however, examination of similar data from a previous investigation (ref. 4) indicated that ignition-limiting inlet pressures were reproducible within about ±3 percent. 3049

The steady-state burning limits of the combustor at the two air-flow rates investigated (1.87 and 3.75 lb/sec/sq ft) were about 6 and 9 inches of mercury absolute, respectively. Sudden changes in the air pressure or fuel flow at these conditions resulted in flame-out; the exhaust temperature was about 150° F. The burning limits are indicated on most of the ignition-data plots.

Air-Gap Ignitors

The relation between the minimum spark energy required for ignition and the combustor-inlet-air total pressure for each of the air-gap ignitors investigated is presented in figures 5 to 9. The performance of each experimental ignitor is compared with that of a reference ignitor (A, fig. 2(a)), which is a current production-type ignitor. The experimental ignition-supply system was used for these tests together with the fixed-area, 80° cone-angle fuel nozzle rated at 10.5 gallons per hour, except where specifically noted otherwise.

Effect of electrode spacing. - The effect of varying the space between the electrodes of reference ignitor A (fig. 2(b)) and experimental ignitor B (fig. 2(c)) on ignition-energy requirements is shown in figure 5. The space between the electrodes was varied from about 0.030 to about 0.235 inch by means of adjustable center electrodes; the maximum spacing investigated was limited by the triggering voltage (10,000 volts) of the ignition-supply system. Variations in the electrode spacing of ignitor A did not affect ignition-energy requirements significantly. Decreases in the electrode spacing of ignitor B increased energy requirements considerably, particularly at spacings less than about 0.060 inch. Also, the energies required with the disk-electrode ignitor B were considerably greater than those required with ignitor A. The data indicate that the large disk electrode of ignitor B introduced a quenching effect which increased energy requirements, particularly at small spacings. These trends and the explanation are substantiated by fundamental studies presented in references 8 and 9.

Effect of spark-gap immersion. - Ignition-energy requirements obtained with the spark gap of ignitor A located outside and inside of the nominal fuel-spray cone angle are shown in figure 6. Extensions were welded to the ignitor electrodes to obtain immersion depths greater than standard (at edge of nominal spray-cone angle); for depths less than standard, shims were used under the ignitor mounting flange. It may be noted from the sketch in figure 6 that increasing the immersion depth also displaced the spark gap further downstream. The data indicate that
3049 the ignition limits were not affected significantly by the depth of immersion as long as the spark gap remained within the fuel-spray cone. Data obtained with the spark gap outside the spray cone indicate somewhat greater energy requirements. A previous investigation (ref. 5) using a different combustor configuration has shown marked effects of immersion depth on ignition characteristics; optimum performance was obtained with the spark gap located at the center line of the combustor.

Combustor design variables have an effect on the optimum spark-gap locations in the combustor. Local air velocity, turbulence, and vaporized fuel-and-air mixture patterns vary in different combustor designs, thus resulting in different optimum spark-gap locations.

In figure 6 it may be noted that the burning limit is at an inlet pressure of about 7 inches of mercury lower than the ignition limit.

Effect of shielding. - Photographs of air-flow patterns in a transparent combustor (ref. 1) showed relatively high local air velocities and large eddies at the ignitor spark gap. Fundamental studies (ref. 10) showed that minimum energy requirements of homogeneous fuel-air mixtures increased as the turbulence and air-flow velocity increased. The effect of decreased air velocities at the spark gap on ignition characteristics was investigated with a number of different ignitor designs (ignitors A, C, D, and E, fig. 2) and a number of variations in ignitor installations (fig. 4). The results of these tests are presented in figure 7.

Figure 7(a) shows the effect of eliminating the 1/16-inch diametral clearance between the body of ignitor A and the combustor liner (fig. 4(b)). It is seen that this reduction in air flow around the ignitor markedly reduced the spark energy required for ignition throughout the combustor-inlet pressure range. Also shown in figure 7(a) are results of further reducing the high-velocity air flow at the spark gap by blocking off the cooling-air opening in the upstream side of the ignitor (fig. 4(c)). Further reduction in ignition-energy requirements throughout the inlet-pressure range resulted. The effect of excess cooling air on ignition is indicated from the results with ignitor C. The high-velocity air introduced around the ignitor offsets any gain in ignition which may have resulted from the auxiliary fuel provided in the ignitor. These results indicate that if the cooling air required for the ignitor is not

permitted to disturb the local fuel-air mixture around the spark gap (velocity and mixture-dilution effects), substantial improvements in ignition characteristics may be realized.

Several special ignitors, designed to reduce the air velocity and turbulence and to improve the fuel-air mixtures at the spark gap, were investigated. The performance of a partially shielded ignitor D (fig. 2(e)) is presented in figure 7(b). The minimum ignition energies were reduced at the combustor pressures investigated; however, there appears to be no gain over ignitor A for pressures below about 13 inches of mer- 3049
cury absolute at the air-flow rate investigated.

The gains obtainable from shielding of the ignitor-spark gap were further demonstrated by the use of experimental ignitor E (no cooling-air hole, fig. 2(f)). The data of figure 7(c) show that appreciable reductions in spark-energy requirements occurred in the upper and intermediate inlet-air pressure range with this ignitor. Apparently, more significant gains were obtained by shielding the ignitor spark gap from high-velocity cooling-air flow than by shielding it from flow disturbances inside the combustor.

Effect of heating elements. - The effect on ignition-energy requirements of electric energy as a source of heat for vaporization of liquid fuel at the spark gap was investigated with ignitors F and G (with a variable-area fuel nozzle). These ignitors (figs. 2(g) and (h)) incorporated nichrome heating elements near the spark gap which were supplied with electric current from either the main ignition source (in the case of ignitor F) or a separate supply system (in the case of ignitor G). The ignition-energy requirements of the combustor equipped with ignitors F and G are shown in figure 8. Test results with ignitor H (ignitor F with heating element removed, as shown in fig. 2(i)) are also included in figure 8. Ignitor F, with heating energy supplied by the ignition system, required excessive total ignition energies (division of energy between heating coil and spark gap is not known). Ignitor G, with a separate energy source for heating, required lower ignition-spark energies than did the reference ignitor A. The separate heating energy (61 watts) was, however, equivalent to about 7.5 joules at 8 sparks per second, which means then that the total energy supplied to ignitor G was also greatly in excess of that required for ignition with reference ignitor A. Furthermore, some of the gains shown by ignitor G over ignitor A may be attributed to absence of cooling-air flow in ignitor G. Removal of the heating element of ignitor F (ignitor H) decreased the ignition-energy requirements. It appears, therefore, that electric energy for ignition was most efficiently used when all the energy was supplied to the ignitor spark gap.

Effect of auxiliary fuel at spark gap. - Previous experience has indicated that the local vapor fuel-air mixtures at the ignitor spark were generally lean; therefore, ignitors C, E, I, and J were designed with

auxiliary fuel feeds to provide a more favorable fuel-air mixture at the electrodes. It was noted previously that any possible gains from auxiliary fuel with ignitor C were more than offset by the use of excess cooling air (fig. 7(a)). The results obtained with ignitors E, I, and J are presented in figure 9. The wire that served as the ground electrode in ignitor E (fig. 2(f)) was replaced with a thin-wall tube of equivalent diameter. This tube then served both as the ground electrode and as a means of supplying a small fuel flow at the spark gap. The test results for ignitor E (fig. 9(a)) show that the use of the auxiliary fuel feed reduced ignition-energy requirements over most of the inlet-air pressure range with this particular design of shielded ignitor. The data of figure 9(a) are for the optimum auxiliary fuel-flow rate, which was about 1.15 pounds per hour.

Ignitors I and J (figs. 2(j) and (k)) were provided with a capillary tube, which fed fuel into a hole in the upstream side of the ignitor shell outside of the combustor air dome. High-velocity air entering the hole may have aided in the atomization and vaporization of the auxiliary fuel (1.15 lb/hr). The resultant fuel-air mixture passed through the body of the ignitor and then flowed through an annular spark gap located either at the end of the ignitor (ignitor I) or at a completely shielded position inside the ignitor body (ignitor J). The performance of these ignitors is presented in figure 9(b). The energy requirements of ignitor I, with the auxiliary fuel feed, were considerably below those of the reference ignitor at most pressures. With no auxiliary fuel feed in ignitor I, the energy requirements were not greatly increased, which indicated that most of the gains may be attributed to the shielding. As the spark annulus was moved into the ignitor body (ignitor J), the ignition energy requirements increased greatly; this increase is probably due to quenching effects. In general, gains obtained from auxiliary fuel feeds at the spark gap were not significant.

Surface-Discharge Ignitors

The surface-discharge ignitors investigated incorporated either solid-ceramic conductors (fired by a nontriggering system) or glazed-surface conductors (fired by a triggering system) between the electrodes. Since ionization of the solid-ceramic ignitors had to be accomplished with relatively low voltages (2000 to 3000 volts), preliminary tests to determine the breakdown voltage requirements of these ignitors at various conditions of operation were first conducted. Figure 10 shows a plot of ignitor breakdown voltage as a function of combustor-inlet air density for the nontriggered ignitors. Ignitor K was not appreciably affected by inlet-air density or by fuel wetting. Ignitor L was considerably affected by both air density and fuel wetting. For an increase in density from 0.026 to 0.089 pound per cubic foot, the breakdown voltage of ignitor L increased from 1500 to 3150 volts when the ignitor was dry; the breakdown

voltage increased to some value above 4700 volts (the limit of the test apparatus) when the electrodes were fuel wetted. Ignitor M was affected by fuel wetting in a similar manner. Poor contact between the semiconductor and the metal electrodes resulting in a series air gap in ignitors L and M may have caused the large increase in breakdown voltage with increase in air density and the sensitivity of the breakdown voltage to fuel wetting. The small fixed-area fuel nozzle and the commercial ignition systems were used to investigate the ignition performance of the solid-ceramic (nontriggered) and the glazed-surface (triggered) experimental ignitors.

3049

Comparison of solid-ceramic ignitors. - The minimum combustor-inlet pressures at which ignition could be obtained with the nontriggered ignitors K, L, and M (fig. 2(l)) are shown in figure 11 as a function of spark energy. There was little or no difference in the ignition limits of the combustor with this group of ignitors, except for the occasional adverse effect of fuel wetting with ignitor L.

Comparison of glazed-surface ignitors. - The glazed-surface ignitors investigated were N through R (fig. 2(l)). Ignitor N was found to be seriously affected by fuel wetting; successful ignition was not obtainable with this ignitor. The effect of electrode spacing on ignition was investigated with the basic design of ignitor O (fig. 2(l)) by using center electrodes of different lengths. The electrode spacing of ignitor O was 0.37 inch, of ignitor P, 0.50 inch, and of ignitor Q, 0.62 inch. The results obtained with these ignitors are shown in figure 12. Although little effect of electrode spacing was observed, the 0.37-inch spacing was slightly superior at the higher air-flow rate; it was also observed that fuel-wetting difficulties were less frequent with this spacing than with the larger spacings.

The minimum ignition pressures of the combustor as a function of spark energy are compared in figure 13 for two glazed-surface ignitors (O and R), for the reference air-gap ignitor, and for an air-gap ignitor S. The performance of ignitor S is included in figure 13 because this ignitor was tested with the same commercial triggered spark system and was similar in geometry to the surface-discharge ignitors. The difference in performance among these ignitors is small, but the ignition limits obtained with the glazed-surface discharge ignitors appears to be slightly better than those obtained with the two air-gap ignitors.

Effect of spark-repetition rate. - The effect of spark-repetition rate on the ignition limits of two surface-discharge ignitors (ignitors O and Q) is presented in figure 14. At a spark energy level of 2.32 joules per spark, the commercial ignition system provided a maximum rate of 3 sparks per second; the minimum rate investigated was 1 spark per 3 seconds. Curve (b) for ignitor Q is considered to be excessively high

because of adverse effects of fuel wetting which were encountered with this ignitor, particularly at the higher air-flow rate. Combustor ignition-pressure limits decreased with an increase in spark-repetition rate (about 1.5 in. Hg for the range of conditions investigated). The trend and order of magnitude of the change in ignition-pressure limits were about the same as those reported in reference 3.

Comparison of best surface-discharge ignitors. - Figure 15 shows a comparison of the combustor-ignition limits obtained with the best surface-discharge ignitors and with reference air-gap ignitor A. All ignitors were fired by the commercial ignition systems. The comparison must necessarily be made on a basis of ignition-limiting pressures attained in a rather narrow range of high-level spark energy, where very small gains are obtained for large increases in spark energy. On this basis the triggered surface-discharge ignitor O appears to be somewhat superior to the nontriggered surface-discharge ignitor K; ignition-limiting inlet pressures attained were 0.5 to 1.0 inch of mercury lower. Both surface-discharge ignitors appear to be slightly superior to the air-gap ignitor A, particularly at the higher air-flow rate.

The superiority of the triggered surface-discharge ignitor over the triggered air-gap ignitor may be the result of differences in (1) the location of the spark, (2) arrangement of cooling-air passages, (3) geometry of the spark, or (4) the efficiency of the discharge circuit with the different ignitors. Almost all the surface-discharge ignitors are superior to ignitor A with respect to cooling-air passages; in ignitor A, the spark gap is fully exposed to the cooling air. It is probable that this ignitor could be redesigned to avoid the adverse effects of the cooling air on ignition; it would appear that more improvement can be gained by this method than by shielding the spark gap from air velocities inside the combustor liner.

Comparison of Ignitors

The ignition limits attained with several of the best air-gap and surface-discharge ignitors with their respective ignition supply systems are compared in figure 16. The gains in ignition performance (at constant ignition-energy levels) resulting from improvements in ignitor design are greater at the higher air-flow rate and at the higher inlet pressures and decrease rapidly as the ignition-limiting inlet pressure is approached. Conversely, improvements in ignitor design result in greater reduction of the spark energy required for ignition (at constant combustor-inlet pressure levels) at low combustor-inlet pressures than at high combustor-inlet pressures. In the range of spark energy at which a comparison can be made (1.25 to 4.5 joules), there appears to be no significant difference in the ignition-limiting pressures attained with the experimental

system with reference ignitor A and those attained with the triggered commercial system with the best surface-discharge ignitor (ignitor O).

Figure 16 shows that ignitor A (with experimental system), installed in the same manner that the surface-discharge ignitors were installed (with partial block of cooling air), had somewhat superior ignition-performance characteristics. It was noted in figure 15, however, that reference ignitor A (with partial block of cooling air), when fired by the commercial triggered systems, was inferior to the surface-discharge ignitors. It would appear, then, that the ignition supply system used influenced the results obtained. A comparison of the results obtained with the same ignitor (reference ignitor A with partial block of cooling air) with the triggered commercial system (fig. 13) and with the experimental system (fig. 7(a)) is presented in figure 17. At the same combustor-inlet pressure, the minimum spark energy required (as measured at the capacitor) with the experimental system (8 sparks/sec) is from 1 to 4 joules less than that required with the commercial system (2 to 7 sparks/sec). From the results presented in figure 17 and from a consideration of the design of the two systems, it is concluded that the portion of the stored energy which is available for ignition at the spark gap is greater for the experimental system than for the commercial system. 3049

It is apparent from the slopes of the ignition-data curves at the high-energy levels and from the indicated burning limits that for this particular combustor with a fuel nozzle rated at 10.5 gallons per hour, successful ignition was not possible at or near the burning limits with the ignitors investigated. The difference between the ignition and burning limits was greater at the higher air-flow rates. In reference 2 where a variable-area fuel nozzle was used, it may be noted that the ignition limits were somewhat lower and the burning limits somewhat higher for this combustor (for a 1-lb Reid vapor-pressure fuel) than those shown in this investigation.

Fuel-Air Mixture Conditions

Effect of fuel spray. - The ignition energy requirements of the single tubular combustor over a range of inlet pressure were determined with a small (10.5 gal/hr) and a large (40 gal/hr) fixed-area fuel nozzle. Both nozzles had a spray-cone angle of 80°. Data were also obtained with a variable-area fuel nozzle with a spray-cone angle of 100° and a nominal flow capacity equal to that of the 40-gallon nozzle. These data are presented in figure 18. The spark energies required for ignition with the large fixed-area nozzle are four to five times those required for the other two nozzles. The limits obtained with the small fixed-area nozzle were similar to those obtained with the variable-area nozzle.

At starting fuel flows, the pressure drop across the large fixed-area nozzle was small (6 lb/sq in.); for the other two nozzles the pressure drops were considerably larger (13 to 44 lb/sq in.). In reference 1, photographs of the fuel spray at starting fuel flows showed that considerably finer atomization was obtained with the variable-area than with the large fixed-area nozzle and also that the spray cone in the combustor was more nearly the same as that observed in still air. Thus, the relatively large ignition-energy requirements for the 40-gallon nozzle may be attributed to the poor fuel atomization and the inadequate fuel distribution obtained with this nozzle.

Effect of inlet-air and fuel temperature. - Tests were conducted to determine the effect of inlet-air and fuel temperature on the ignition characteristics of the single tubular combustor. The results are presented in figure 19, in which required spark energy is plotted as a function of combustor-inlet pressure for two inlet temperatures and two air-flow rates. Increasing the inlet temperature from 10° to 145° F decreased the ignition-energy requirements considerably at all pressures investigated. These results were obtained with the experimental ignition system and ignitor A. The effect of inlet temperature on ignition limits was also investigated with the commercial ignition system and ignitor O at a constant spark-energy level of 2.12 joules. The results, presented in figure 20, show that as the inlet temperature was increased from -40° to 140° F, the ignition-limiting pressure decreased from 11.5 to 8 inches of mercury absolute. It is apparent that an increase in the inlet-air and fuel temperature has a very beneficial effect on ignition.

Effect of fuel volatility. - Combustor ignition tests were conducted with two fuels of different volatility and with the surface-discharge ignitor O; the results are presented in figure 21. The required spark energy is plotted as a function of inlet pressure for a 1-pound and a 2.7-pound Reid vapor pressure fuel (JP-4, table II). There is an improvement in ignition characteristics (lower ignition-limiting pressure) with increased fuel volatility at both air-flow rates. These results substantiate trends observed by a number of investigators (e.g., ref. 4).

SUMMARY OF RESULTS

From an investigation to determine the effect of ignitor design and ignitor-gap environment on ignition in a single tubular turbojet-engine combustor using high-energy variable-capacitance spark systems, the following results were obtained:

1. Shielding the ignitor spark gap from high-velocity ignitor cooling-air flow resulted in the largest reduction in ignition-energy requirements of an air-gap ignitor. The use of heating elements near the

electrodes and auxiliary fuel feeds at the ignitor spark gap showed little or no promise as ignition aids. Electrode spacing of the air-gap ignitor had a minor effect on ignition-energy requirements in the range investigated (0.030 to 0.235 in.).

2. No significant difference in ignition limits was observed with three different designs of surface-discharge ignitors having solid-ceramic semiconductors between the electrodes. Similarly, there was little or no difference in ignition limits with several ignitors having semiconductive coatings (glazed) between the electrodes. The ignition-limiting (combustor-inlet air) pressures for the best of the triggered ignitors (glazed semiconductive coatings) were 0.5 to 1.0 inch of mercury lower than those attained with the best nontriggered ignitors (solid-ceramic semiconductors) when fired by their respective ignition systems.

3049

3. With the same ignition supply system used, the combustor-inlet pressures at the ignition limit were 1 to 2 inches of mercury lower for the best of the surface-discharge ignitors than for a reference production-type air-gap ignitor. In general, the surface-discharge ignitors, particularly those with wide spark gaps, were more subject to adverse effects of fuel wetting than conventional air-gap ignitors.

4. The ignition characteristics of a production-type air-gap ignitor, modified to eliminate the cooling-air flow, were somewhat superior to those of the best surface-discharge ignitor (each with its respective energy supply system).

5. Both the fuel flow and the spark-energy requirements for ignition were considerably reduced by the use of fuel nozzles providing improved atomization and distribution of fuel droplets. Previously observed trends of lower ignition-pressure limits with increased fuel volatility, increased spark-repetition rate, and increased fuel and air temperature were observed in this investigation.

CONCLUDING REMARKS

A large number of factors which affect the ignition characteristics of turbojet-engine combustors were investigated. The results obtained indicate some general design principles for ignitors and ignition systems.

The high energies required for ignition of turbojet-engine combustors at adverse inlet conditions were satisfactorily supplied by capacitance-type systems. It was noted in the investigation that the portion of the stored energy (in the capacitor) which is available for ignition at the spark gap varied with different ignition systems. The elimination of energy losses due to some components of the capacitance-type system would decrease the amount of stored energy required and,

hence, the weight and size of the system. With either type of ignitor, a barrier gap in the ignition circuit provides a safety measure against electric shock and also an aid in preventing misfiring of carbon-fouled ignitors; however, it is reputed to be a large factor in energy losses in the circuit.

The low-voltage nontriggered ignition system avoids some of the problems associated with the high-voltage ionization circuit such as dielectric losses, corona, and flash-over. The observed sensitivity of surface-discharge ignitors to fuel wetting can probably be overcome by providing a good contact between the electrodes and the semiconductive material.

The investigation of the effect of spark-gap environment variables on ignition limits indicates that reduction in the energy required for ignition can be obtained through ignitor, combustor, and fuel-spray nozzle design. Providing low local-air velocity and turbulence, fine fuel atomization, and near-optimum local fuel-air ratio will appreciably lower the ignition energy required for a particular combustor-inlet condition or provide better ignition characteristics for a particular spark-energy level. The favorable environment for ignition may, however, increase local carbon formation during combustion. Use of a nontriggered ignition system and a surface-discharge-type ignitor in combination with controlled ignitor spark-gap environment may provide optimum design for ignition.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 19, 1954

APPENDIX - IGNITION SYSTEMS

Simplified circuit diagrams of the three basic ignition systems used are shown in figures 22 and 23; all were of the low-voltage, high-energy capacitance type. Two of the three systems (figs. 22 and 23(a)) incorporated triggering circuits; that is, a high-voltage (10 to 20 kv) spark of low energy is first discharged to ionize the gap for passage of the second high-energy, low-voltage spark. The third ignition system (fig. 23(b)) was of the nontriggered type, designed to avoid some of the problems associated with the high-voltage ionization circuit, such as dielectric losses, corona, and flash-over. With the third system, the space between the ignitor electrodes must contain a semiconductive material that will provide a spark path for the low-voltage high-energy discharge. A description of the early development of the surface-discharge ignitor system may be obtained from references 11 to 13. 3049

Experimental ignition system (fig. 22). - The laboratory experimental ignition system was of the variable-voltage, variable-capacitance type (triggered) with a spark-energy range of from 0.006 to over 10 joules per spark. Its sparking rate was held constant at 8 sparks per second. This system was used in the ignition studies reported in reference 4. Inasmuch as weight and space were not considerations in the experimental unit, losses associated with small, compact, light-weight (barrier-gap) commercial ignition systems were minimized. The condenser voltage was measured by a calibrated direct-current oscilloscope which showed maximum and minimum voltages during sparking. The cable connecting the unit to the ignitor was about 30 inches long.

Commercial ignition systems (fig. 23). - The commercial triggered, variable-capacitance spark system used in this investigation is shown in figure 23(a). Power was supplied by a 24-volt battery through a circuit (including a radio noise filter and a vibrator) to the primary coil of transformer A. The output of transformer A, after being rectified, charged a storage capacitor as well as a trigger capacitor. The discharge of the trigger capacitor through the sealed barrier gap is stepped up by a pulse transformer from about 3000 to about 20,000 volts, which is sufficient to ionize the ignitor spark gap. After the ignitor gap has been ionized, the storage condenser discharges the high energy through the sealed barrier gap and the secondary winding of the pulse transformer. A coaxial cable (56 in. long) connected this triggered unit with its ignitor plug. The spark duration was about 70 microseconds for this system.

Operation of the nontriggered unit (fig. 23(b)) was similar to that of the triggered unit except that no ionization pulse was included. This spark system would not, therefore, operate ignitors requiring breakdown voltages greater than 3000 volts. An essential component of such a system is a means of isolating the semiconductive ignitor gap from the storage condenser while the condenser is being charged. The sealed spark gap

in the circuit served this purpose. The spark duration for this unit was about 40 microseconds. (The coaxial cable for this nontriggered system was 42 in. long.)

To permit a voltage calibration of the two commercial systems, a relay was placed in series with a barrier gap which prevented triggering and, hence, prevented discharge of the condenser. With reduced input from the battery and no condenser discharge, a steady-charge voltage existed on the storage condenser, and a voltmeter indicated this voltage directly across the condenser. At the same time, a direct-coupled oscilloscope was calibrated by comparison with the voltmeter. Thereafter, the oscilloscope was used to indicate peak condenser voltage during normal operation; it could be switched to any of the five storage condensers.

The spark repetition rates were determined with a stop watch for rates of about 2.5 sparks per second and below; for higher rates, a Lissajous figure on the oscilloscope screen was used; a signal generator supplied the X-deflection or horizontal component of the figure.

Both the triggered and nontriggered units delivered essentially a uniform, repeatable barrier-gap voltage of 3000 volts for a range of battery-input voltage from 14 to 30 volts. A change in spark energy would, however, cause a change in the spark repetition rate, as shown in figure 24. A spark repetition-rate-control rheostat was placed in series with the battery so that the rate could be varied if desired. In most cases, however, the full battery voltage (and, therefore, the maximum spark repetition rate) was used.

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9. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Academic Press, Inc. (New York), 1951, pp. 390-424.

10. Swett, Clyde C., Jr., and Donlon, Richard H.: Spark Ignition of Flowing Gases. III - Effect of Turbulence Promoter on Energy Required to Ignite a Propane-Air Mixture. NACA RM E52J28, 1953.

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12. Tognola, Tullio: Advantages and Disadvantages of the Surface Gap Ignition System as Applied to Reciprocating Engines. Minutes of Bendix Ignition and Engine Analyzer Conference (New York), June 24-26, 1952, pp. 60-63.

13. Anon.: High-Energy Ignition System for Gas-Turbine Starting. Rotax Ltd., London (England).

CT-3 back 3049

TABLE I. - IGNITORS

Ignitor		Electrode spacing, in.	Semi-conductor	Trig-gered	Ignition system	Design principle
Letter	Code					
A	F99	0.070	None	Yes	Experimental	Reference ignitor
B	---	0.030 to 0.20	None	Yes	Experimental	Effect of electrode spacing
C	---	.070	None	Yes	Experimental	Shielding plus auxiliary fuel
D	---	.070	None	Yes	Experimental	Shielding
E	---	.070	None	Yes	Experimental	Shielding
F	---	.070	None	Yes	Experimental	Heating
G	---	.070	None	Yes	Experimental	Shielding plus heating
H	---	.070	None	Yes	Experimental	Shielding, no heating
I	---	.070	None	Yes	Experimental	Shielding plus auxiliary fuel
J	---	.070	None	Yes	Experimental	Shielding plus auxiliary fuel
K	FHE-1-X20	.010	Solid ceramic	No	Commercial	Surface discharge
L	FHE-1-X23	.10	Solid ceramic	No	Commercial	Surface discharge
M	FHE-1-X6	.10	Solid ceramic	No	Commercial	Surface discharge
N	FS-27-X2	.51	Conducting glaze	Yes	Commercial	Surface discharge
O	FS-27-X4	.37	Conducting glaze	Yes	Commercial	Surface discharge
P	FS-27-X4	.50	Conducting glaze	Yes	Commercial	Surface discharge
Q	FS-27-X4	.62	Conducting glaze	Yes	Commercial	Surface discharge
R	FS-27-X5	.50	Conducting glaze	Yes	Commercial	Surface discharge
S	FS-27-X3	.10	None	Yes	Commercial	-----------------

3049

TABLE II. - FUEL ANALYSIS

Fuel properties	Modified MIL-F-5624A (1-lb fuel)	MIL-F-5624A grade JP-4 fuel
	NACA fuel 50-197	NACA fuel 52-288
A.S.T.M. distillation D86-46, °F		
Initial boiling point	181	139
Percentage evaporated		
5	242	224
10	271	253
20	300	291
30	319	311
40	332	324
50	351	333
60	356	347
70	381	363
80	403	382
90	441	413
Final boiling point	508	486
Residue, percent	1.2	1.2
Loss, percent	0.2	0.7
Reid vapor pressure, lb/sq in.	1.0	2.7
Hydrogen-carbon ratio	0.170	0.168
Heat of combustion, Btu/lb	18,691	18,675
Specific gravity	0.780	0.776
Freezing point, °F	<-76	<-76
Viscosity (100° F), centistokes	1.05	0.935

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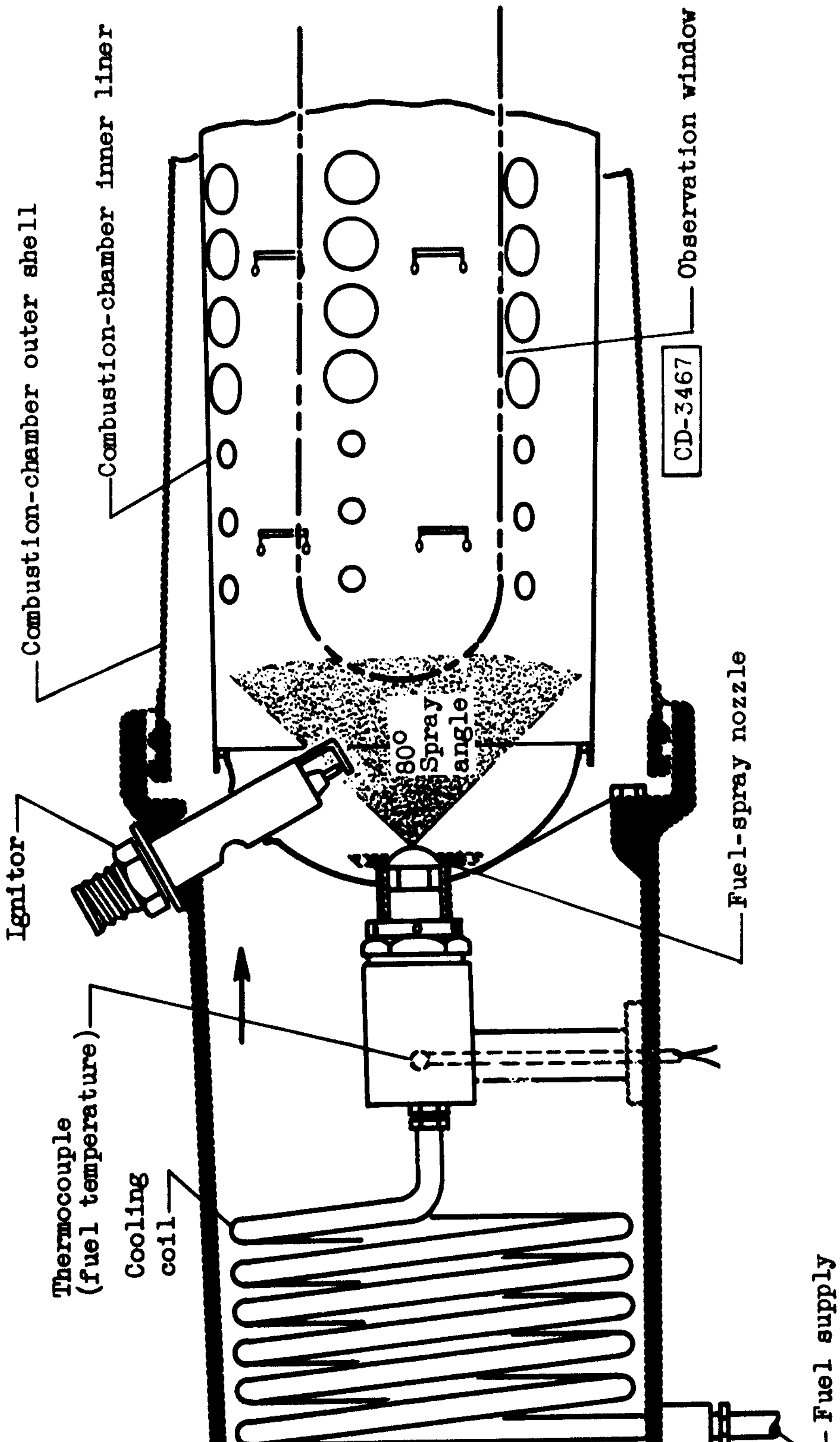

Figure 1. - Diagrammatic cross section of single tubular combustor (ref. 4).

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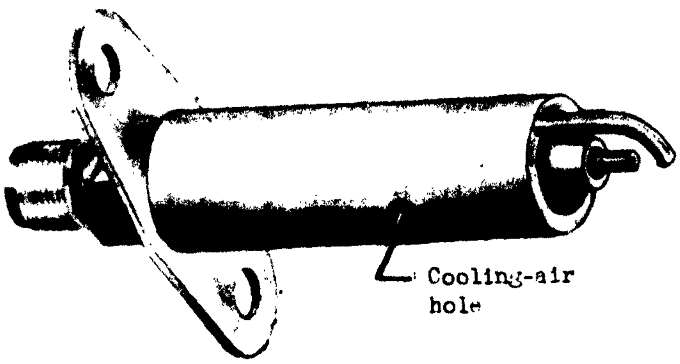

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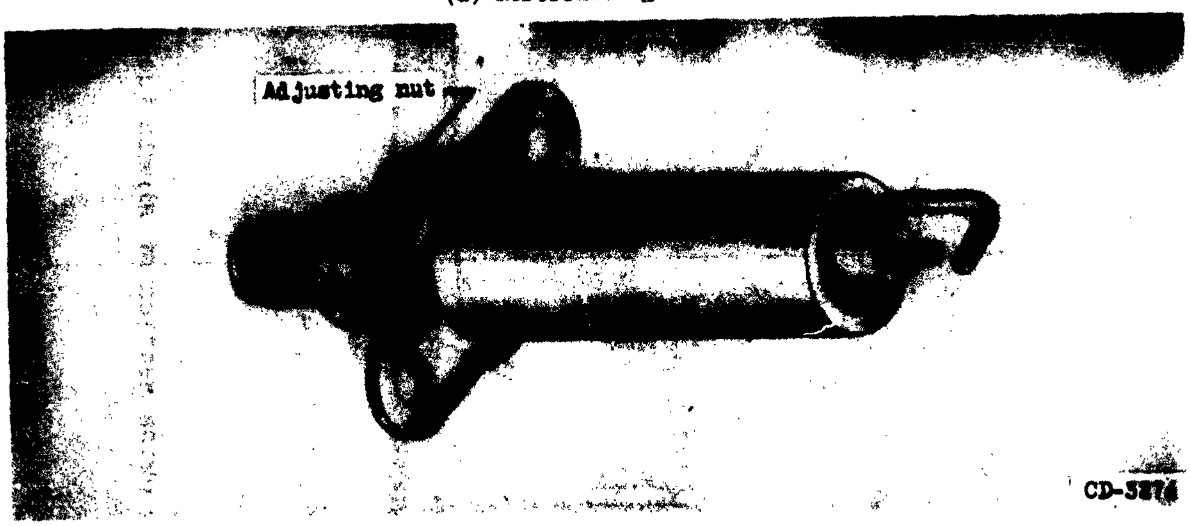
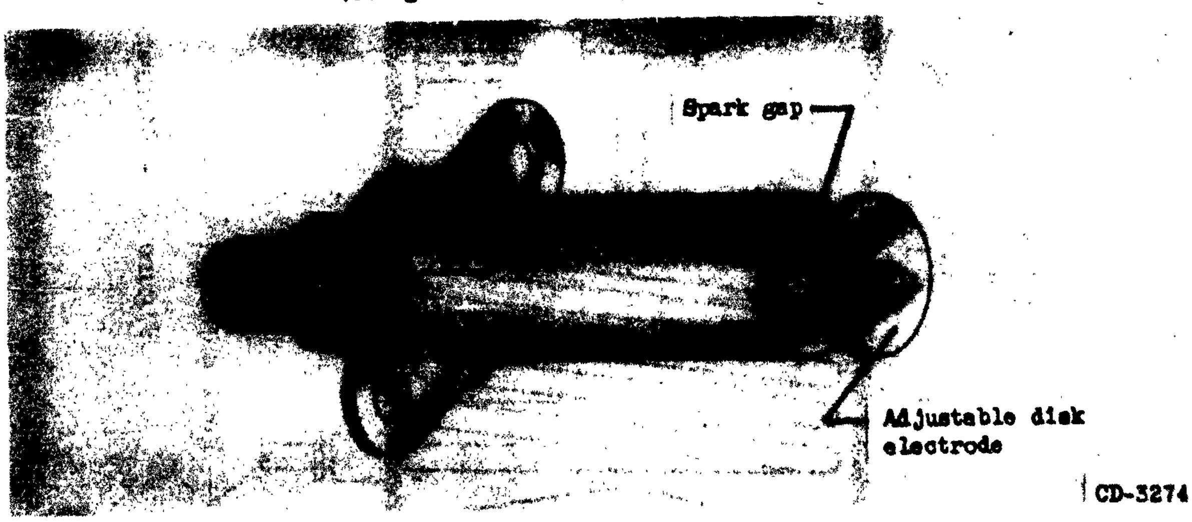
(a) Reference ignitor A.



(b) Ignitor A with adjustable spark gap.



(c) Ignitor B.

Figure 2. - Experimental ignitors.

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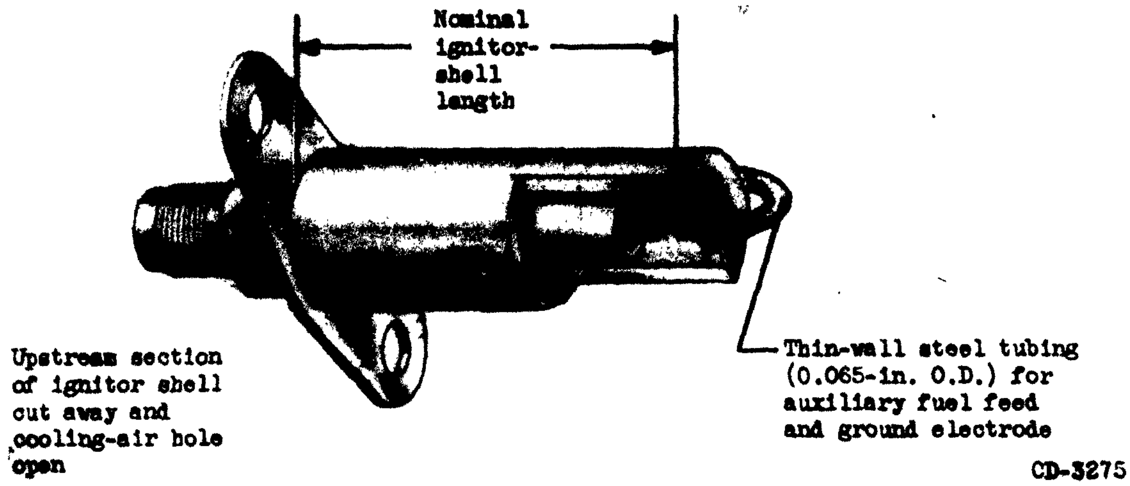
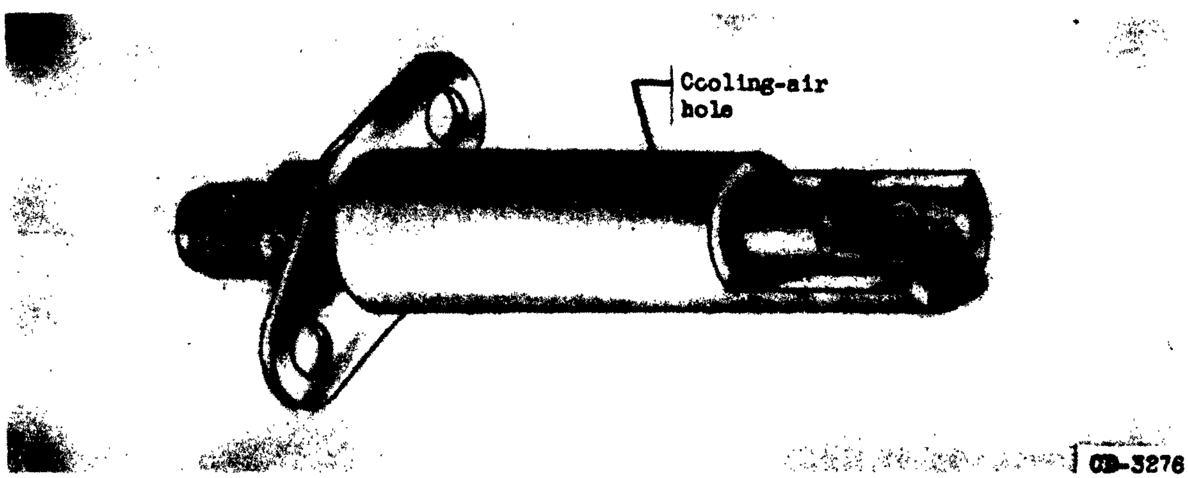
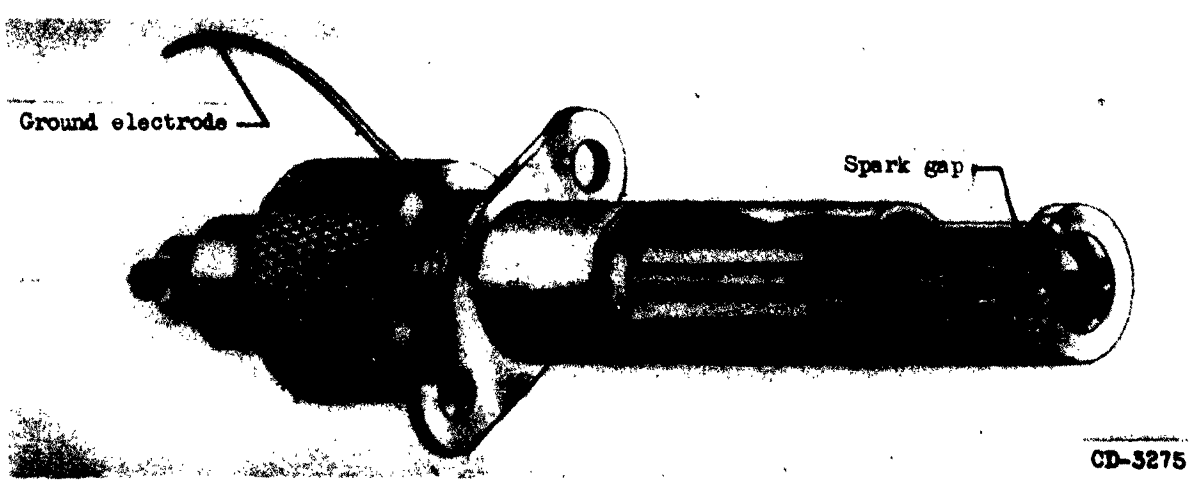


(d) Ignitor C.



(e) Ignitor D (partial shield).



(f) Ignitor E (no cooling-air hole).

Figure 2. - Continued. Experimental ignitors.

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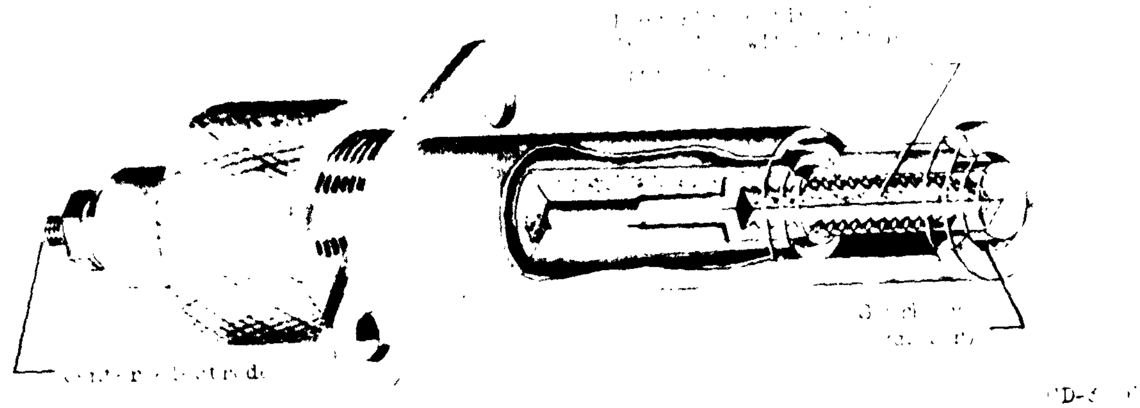
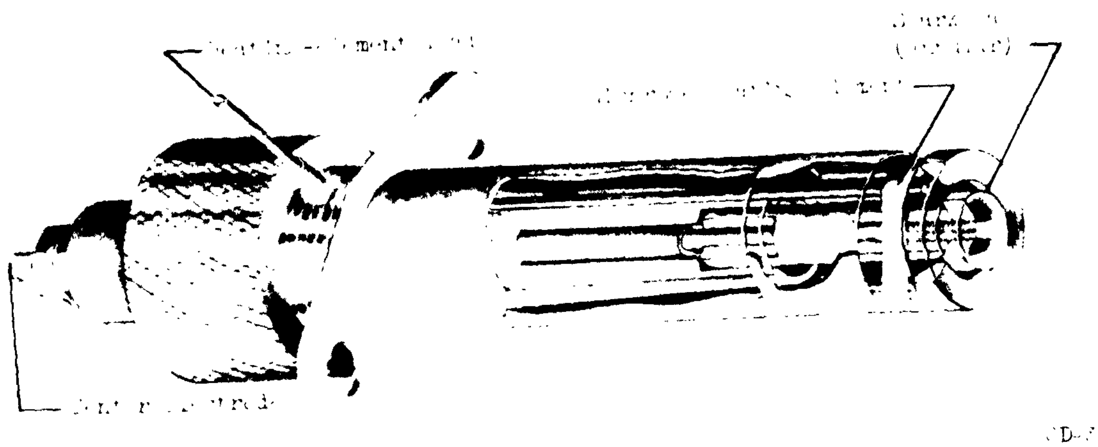
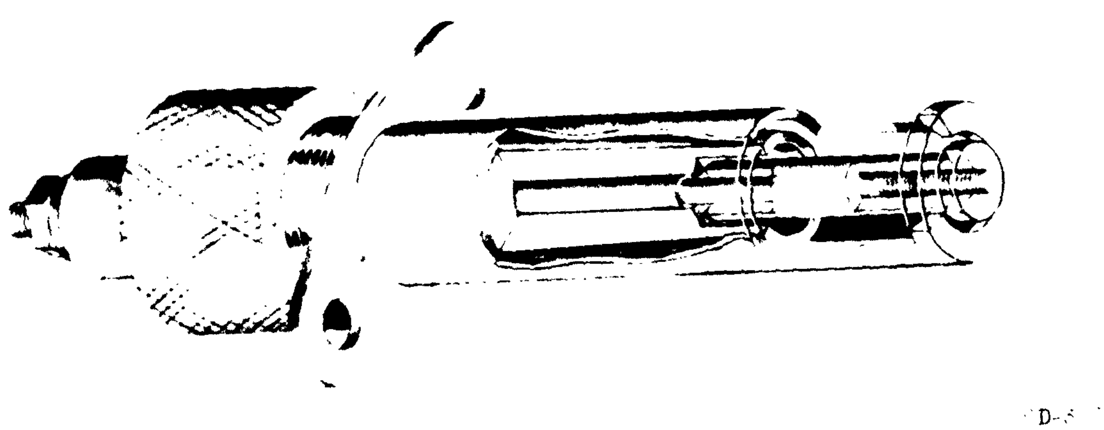


(g) Ignitor F (no cooling-air hole).

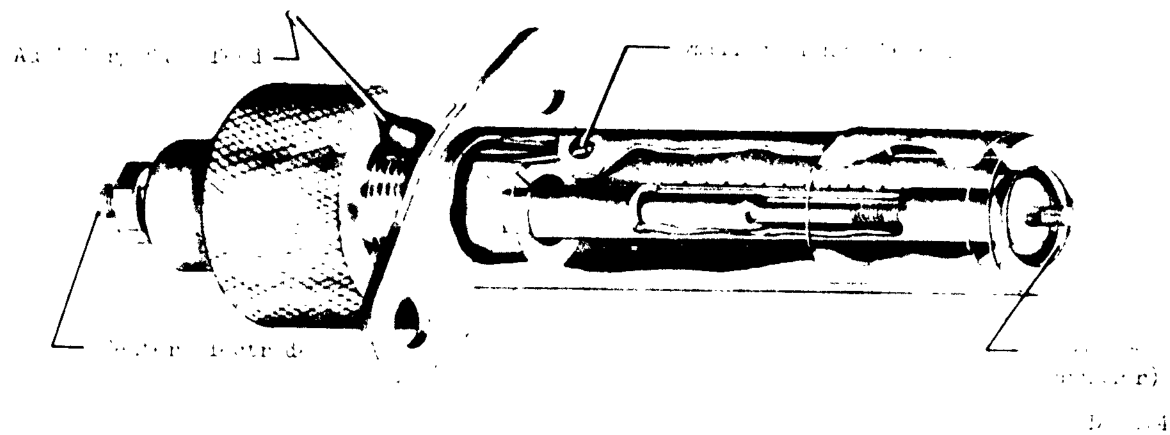


(h) Ignitor G (no cooling-air hole).

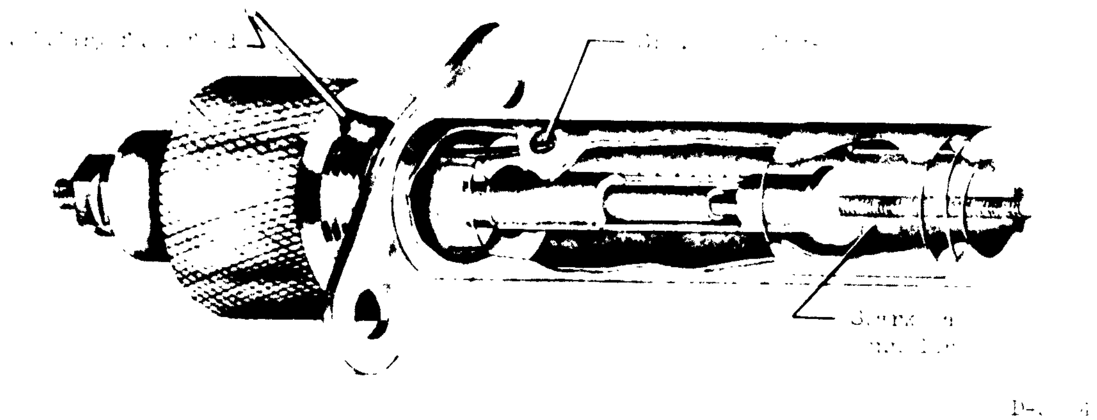


(i) Ignitor H (no heating element, no cooling-air hole).

Figure 2. - Continued. Experimental ignitors.



(j) Ignitor [illegible] (full shield).



(k) Ignitor J (full shield).

Figure 2. - Continued. Experimental ignitors.

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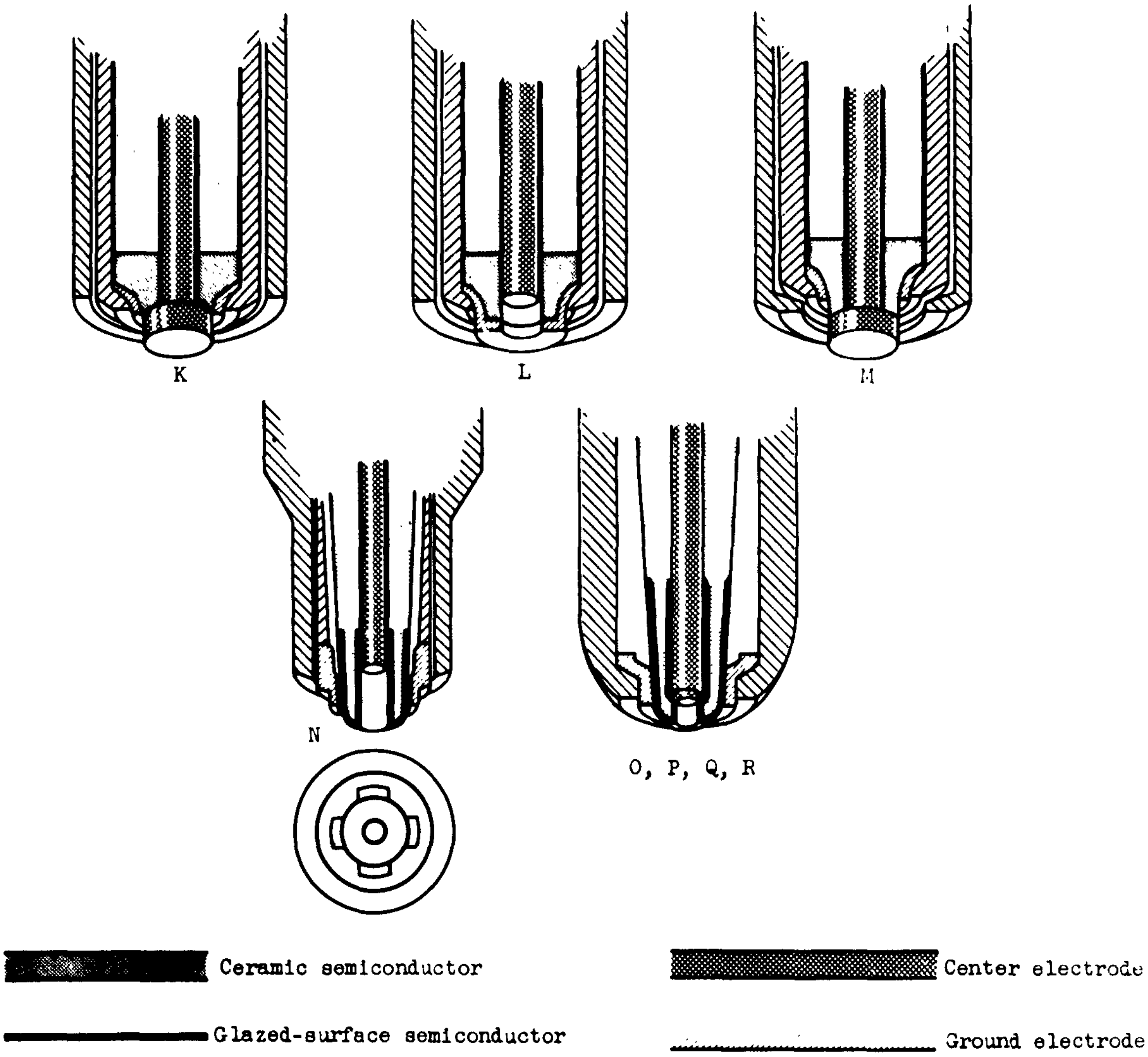
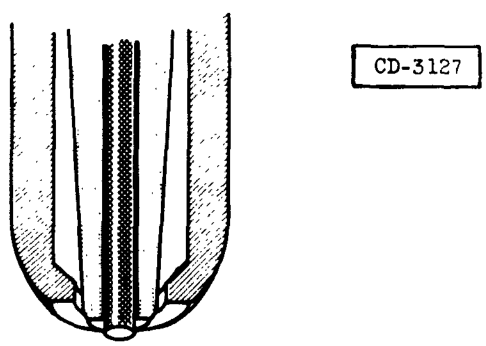


(*l*) Sectional views of experimental surface-discharge ignitors. (Cooling-air entrance in outer shell of ignitors.)



(m) Sectional view of experimental air-gap ignitor S. (Cooling-air entrance in outer shell of ignitor.)

Figure 2. - Concluded. Experimental ignitors.

CT-4 back 3049

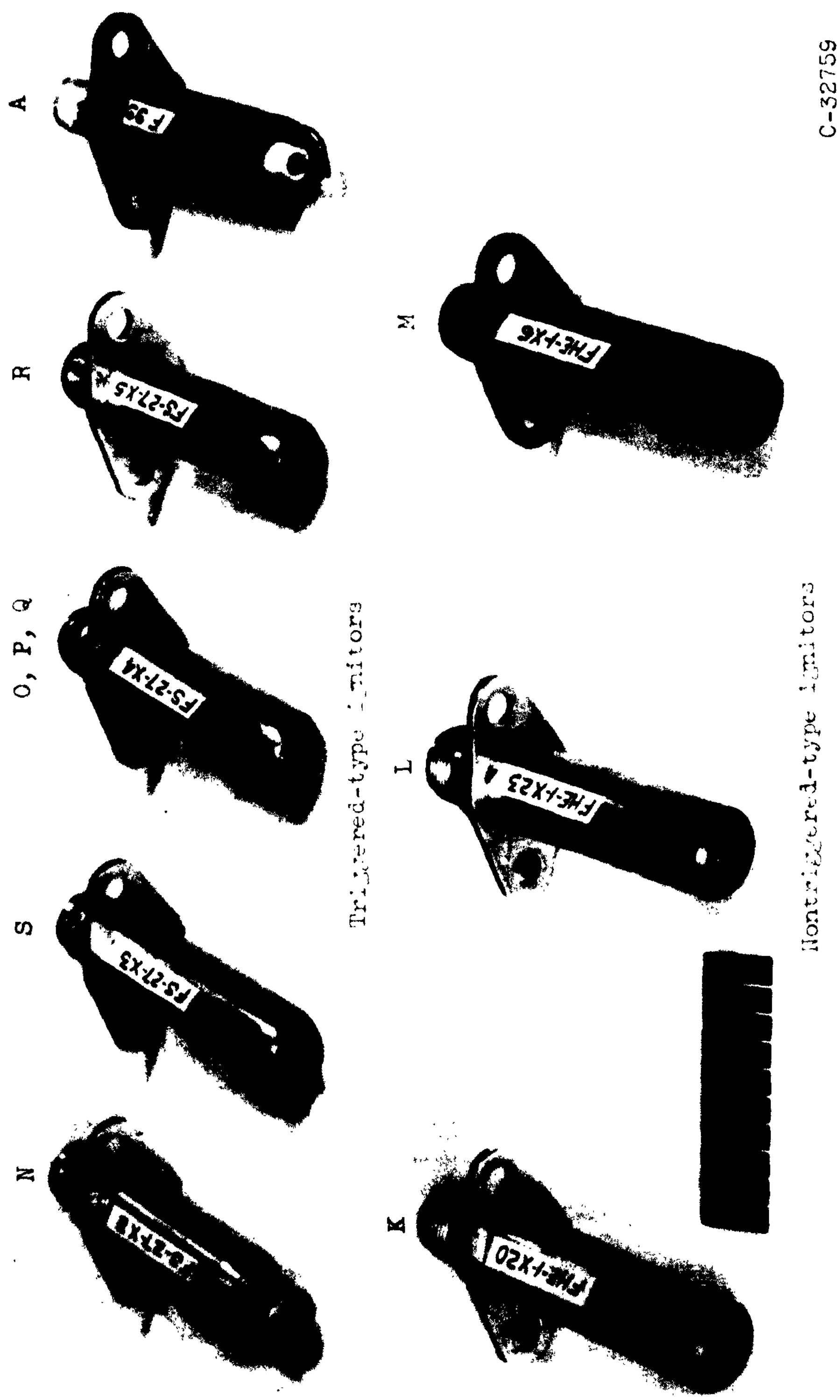
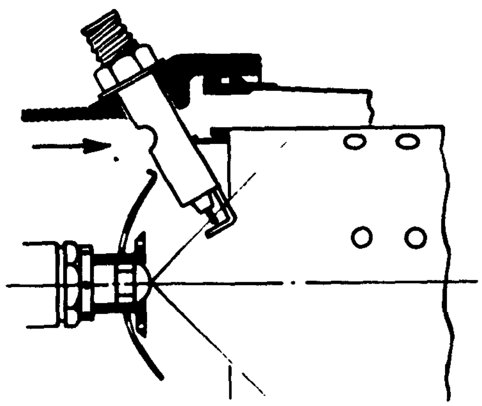
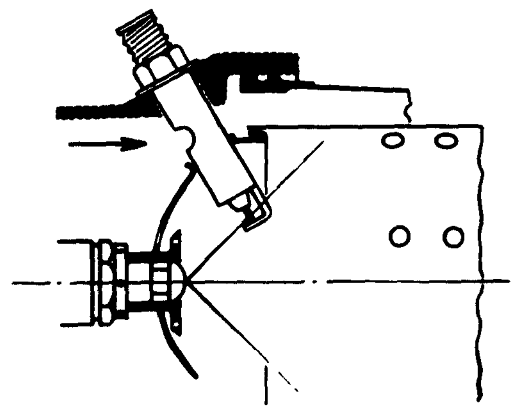


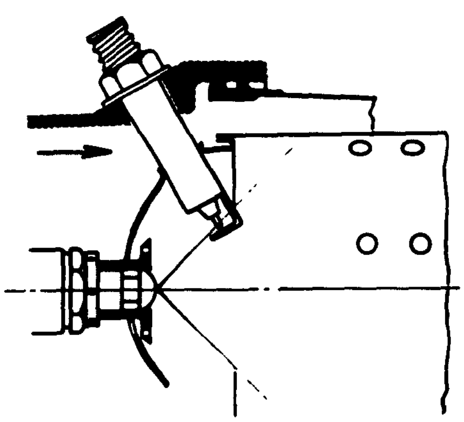
Figure 3. - Experimental ignitors K through R; reference ignitor A.



(a) Standard installation; $\frac{1}{16}$-inch diametral clearance between ignitor and combustor; cooling-air hole open.



(b) Cooling-air reduced; diametral clearance reduced to zero.



(c) No cooling air; no diametral clearance or cooling-air hole.

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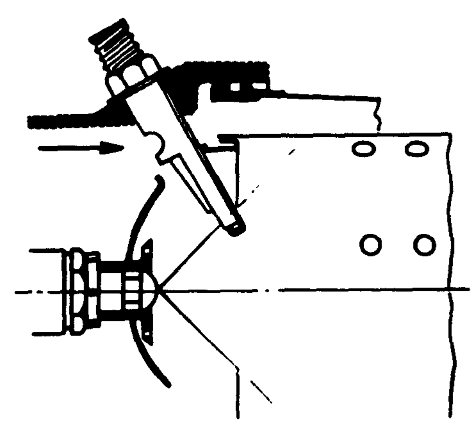

(d) Excess cooling air; (ignitor C).

Figure 4. - Ignitor installations to obtain varied amounts of cooling air. Ground electrode shown 90° from standard position except for ignitor C.

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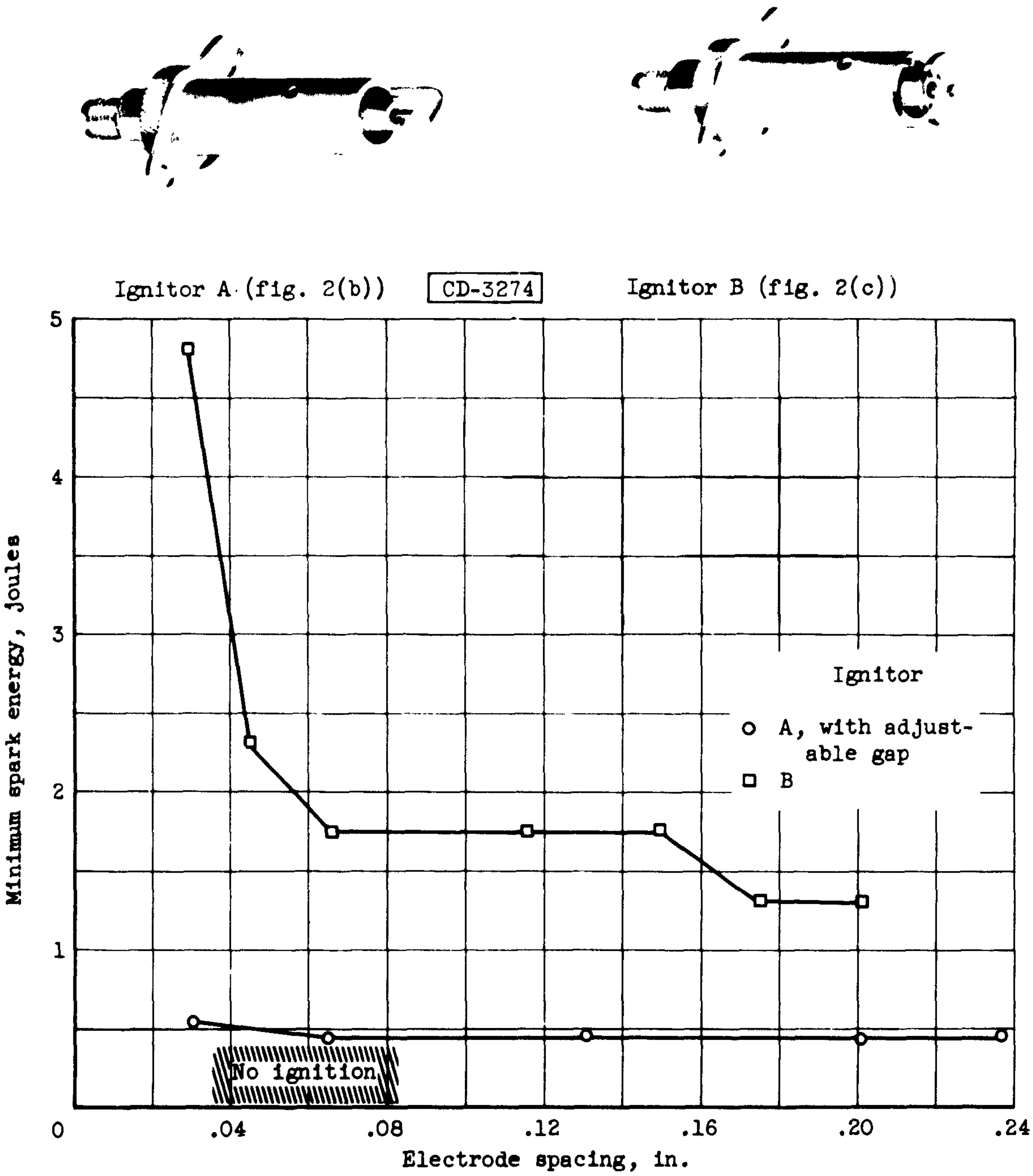

Figure 5. - Effect of electrode spacing on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air pressure, 12 inches of mercury absolute; air flow, 1.87 pounds per second per square foot; inlet-air and fuel temperature, 10° F.

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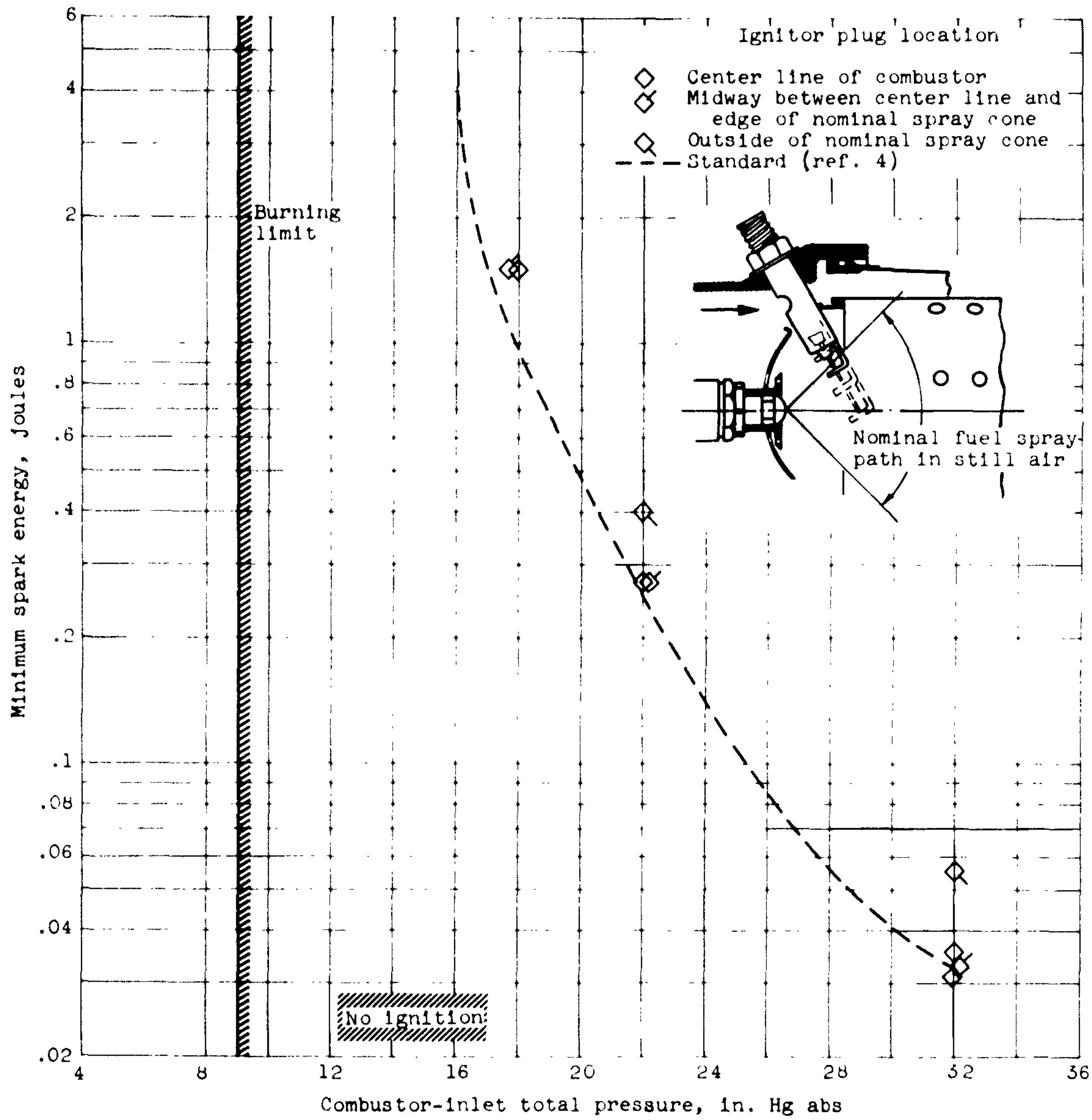

Figure 6. - Effect of spark-gap immersion depth on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; air flow, 3.75 pounds per second per square foot; inlet-air and fuel temperature, 10° F.

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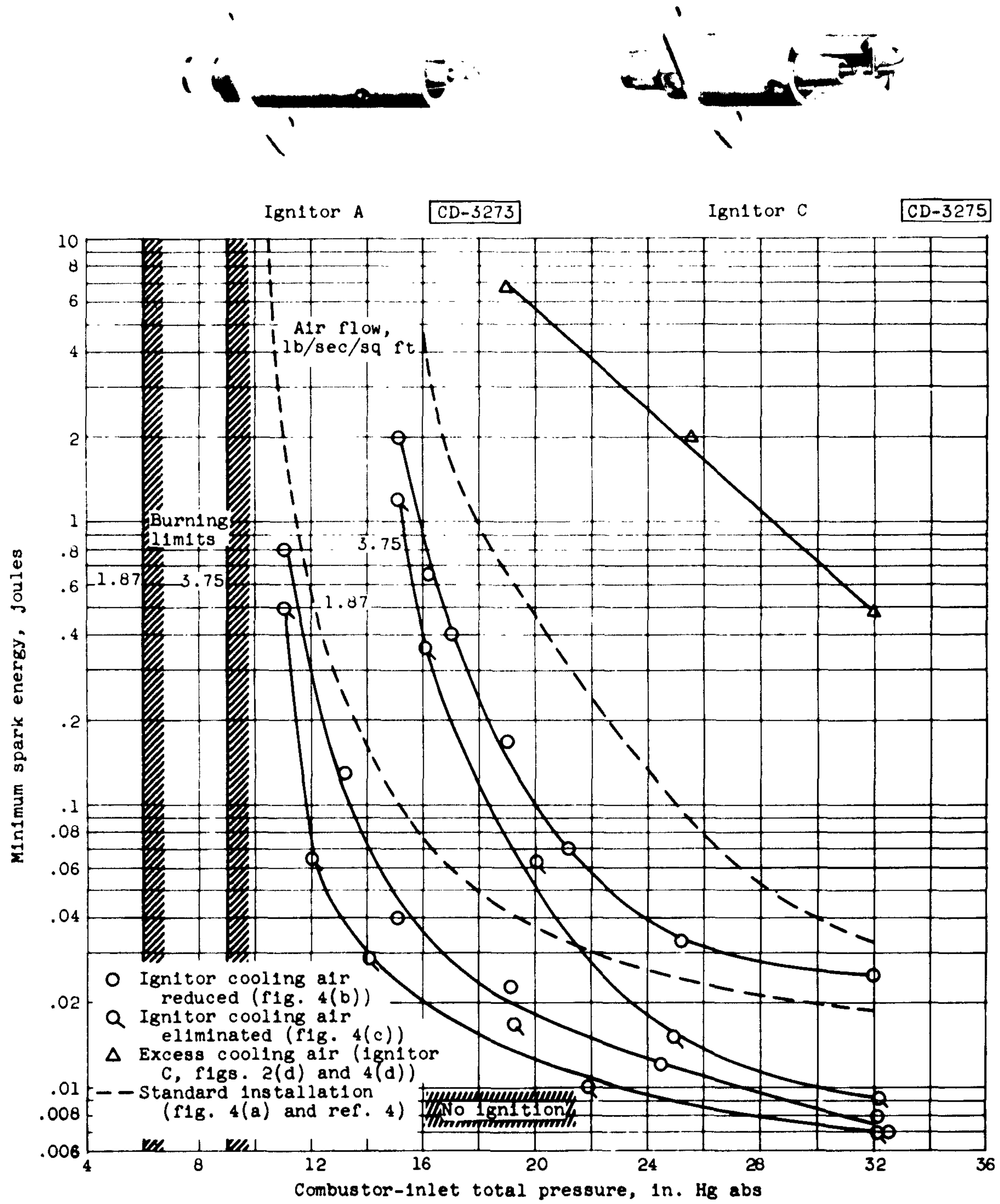
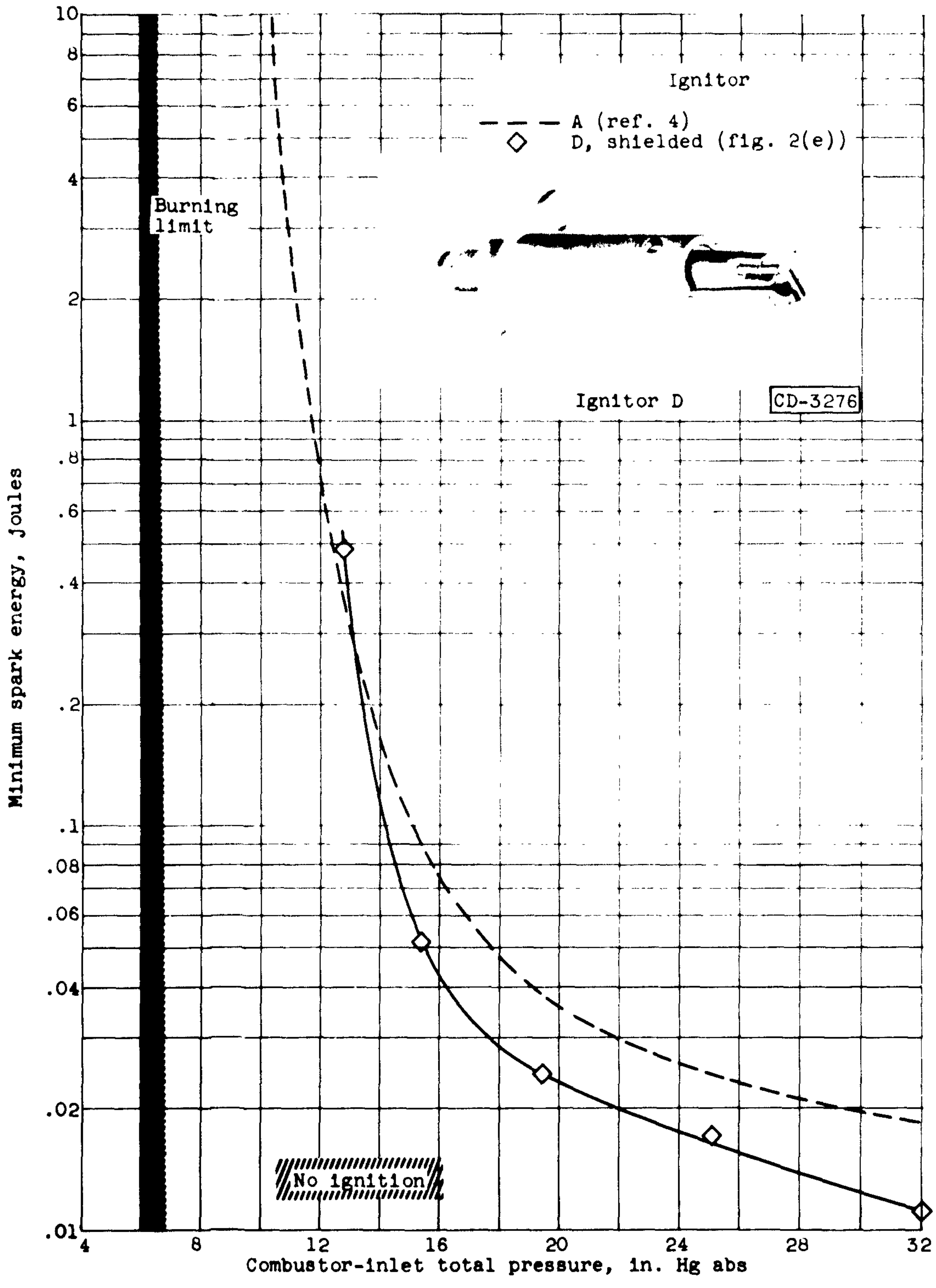


(a) Ignitors A and C; air flow, 1.87 and 3.75 pounds per second per square foot.

Figure 7. - Effect of air flow at spark gap on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.



(b) Ignitor D; air flow, 1.87 pounds per second per square foot.

Figure 7. - Continued. Effect of air flow at spark gap on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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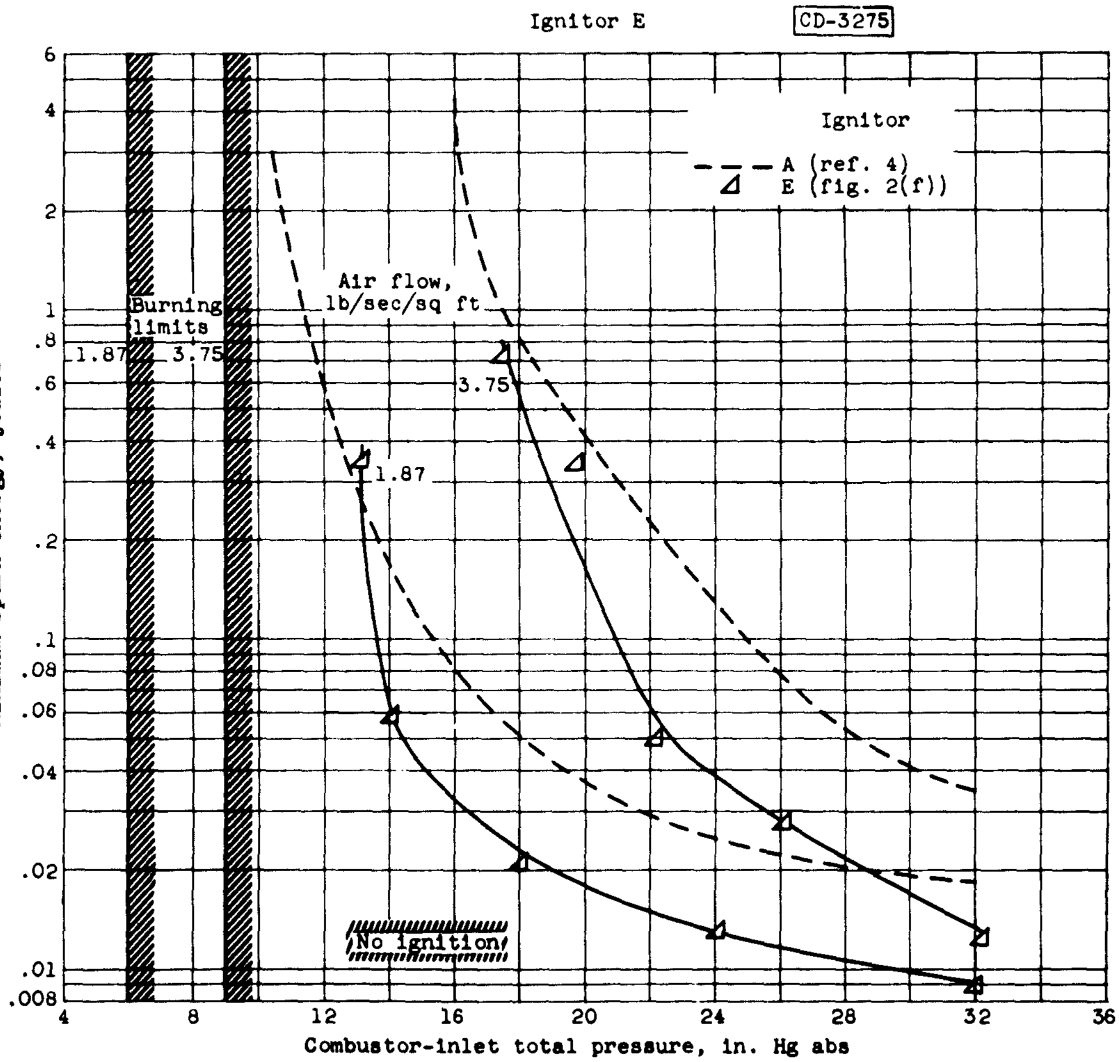
CT-5 3049



(c) Ignitor E; air flow, 1.87 and 3.75 pounds per second per square foot.

Figure 7. - Concluded. Effect of air flow at spark gap on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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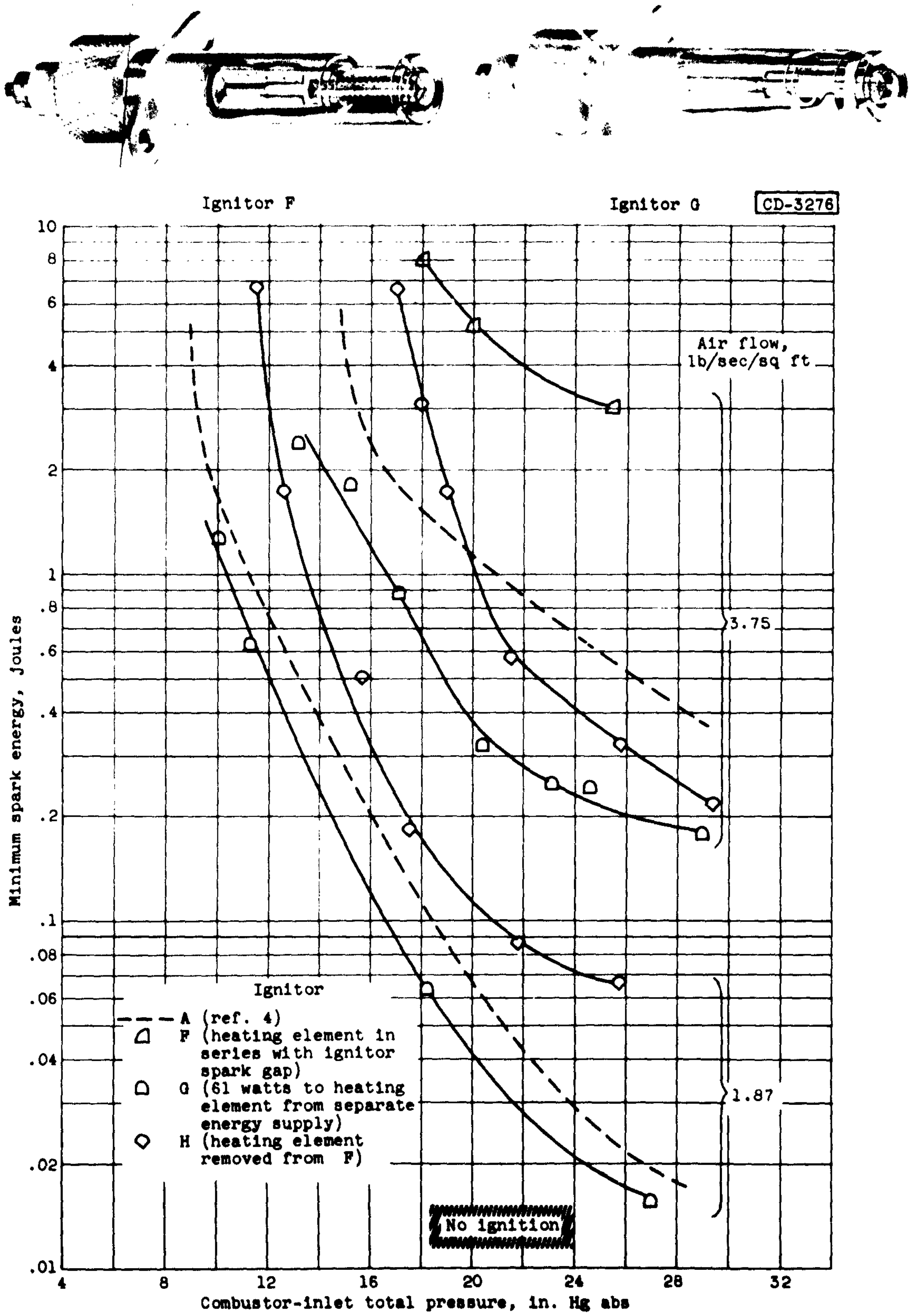

Figure 8. - Effect of fuel heating at spark electrodes on ignition-energy requirements of single tubular combustor. Fuel-spray nozzle, variable-area type; experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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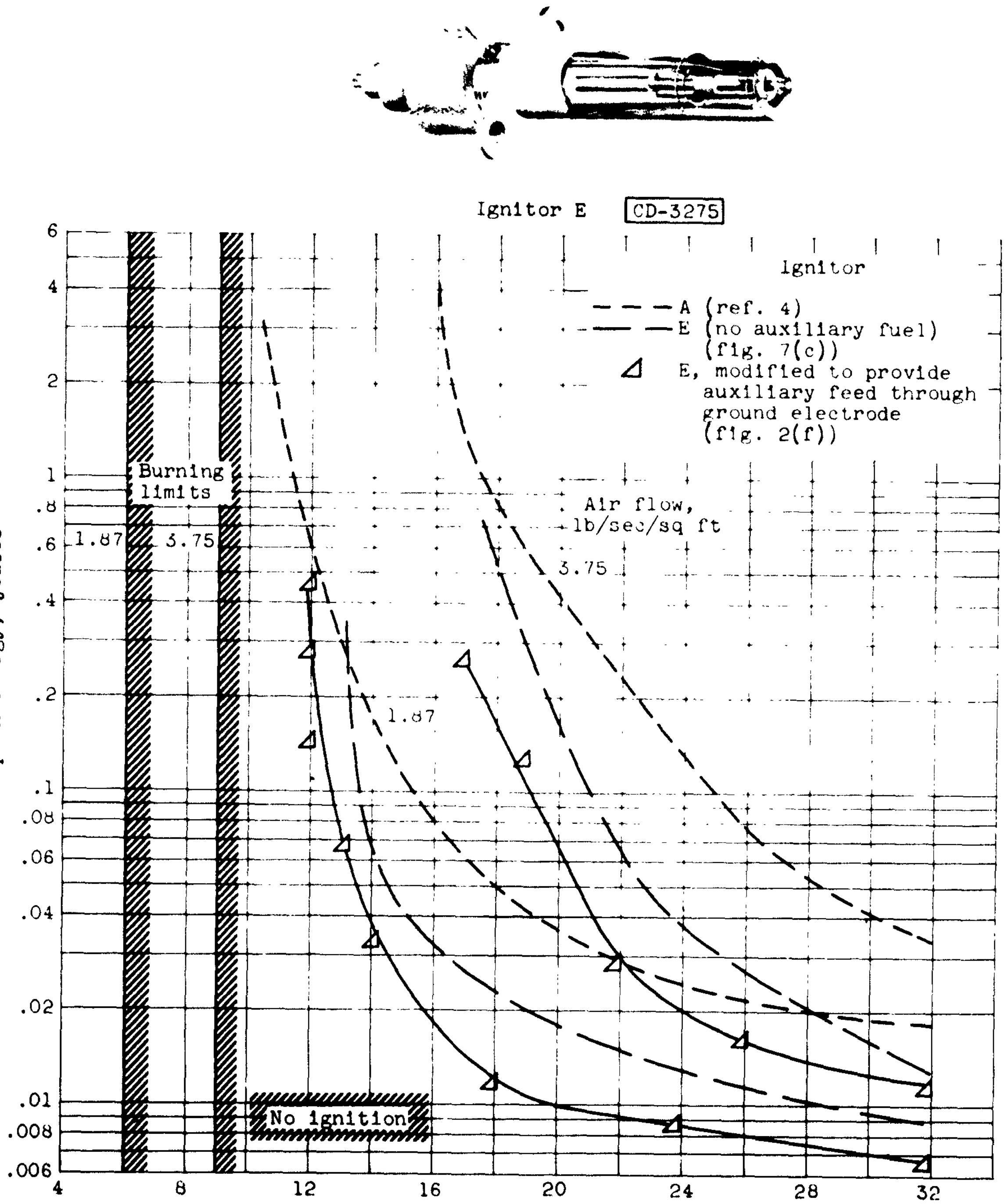

(a) Ignitor E modified; air flow, 1.87 and 3.75 pounds per second per square foot.

Figure 9. - Effect of auxiliary fuel at spark electrodes on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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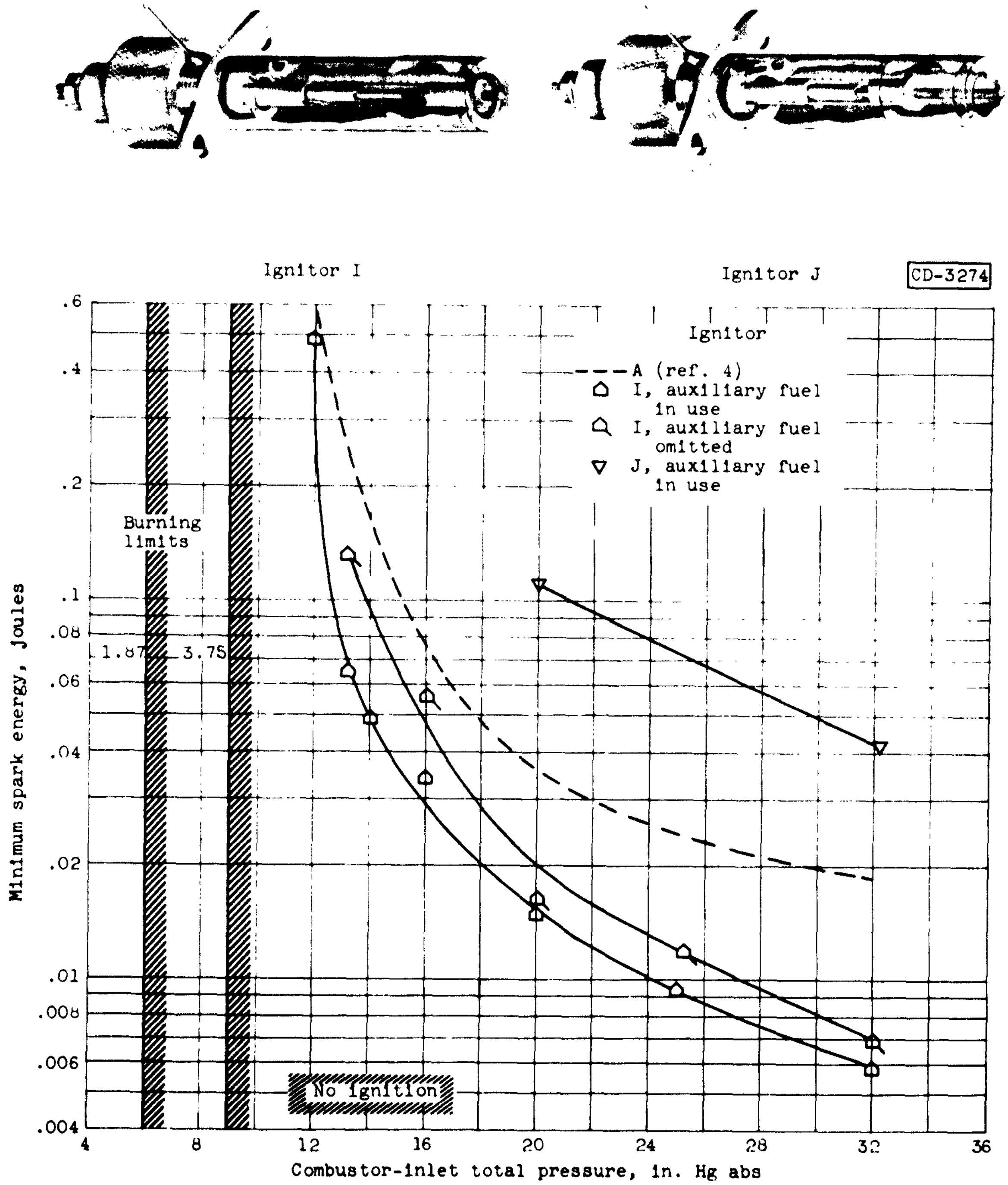

(b) Ignitors I and J; air flow, 1.87 pounds per second per square foot.

Figure 9. - Concluded. Effect of auxiliary fuel at spark electrodes on ignition-energy requirements of single tubular combustor. Experimental ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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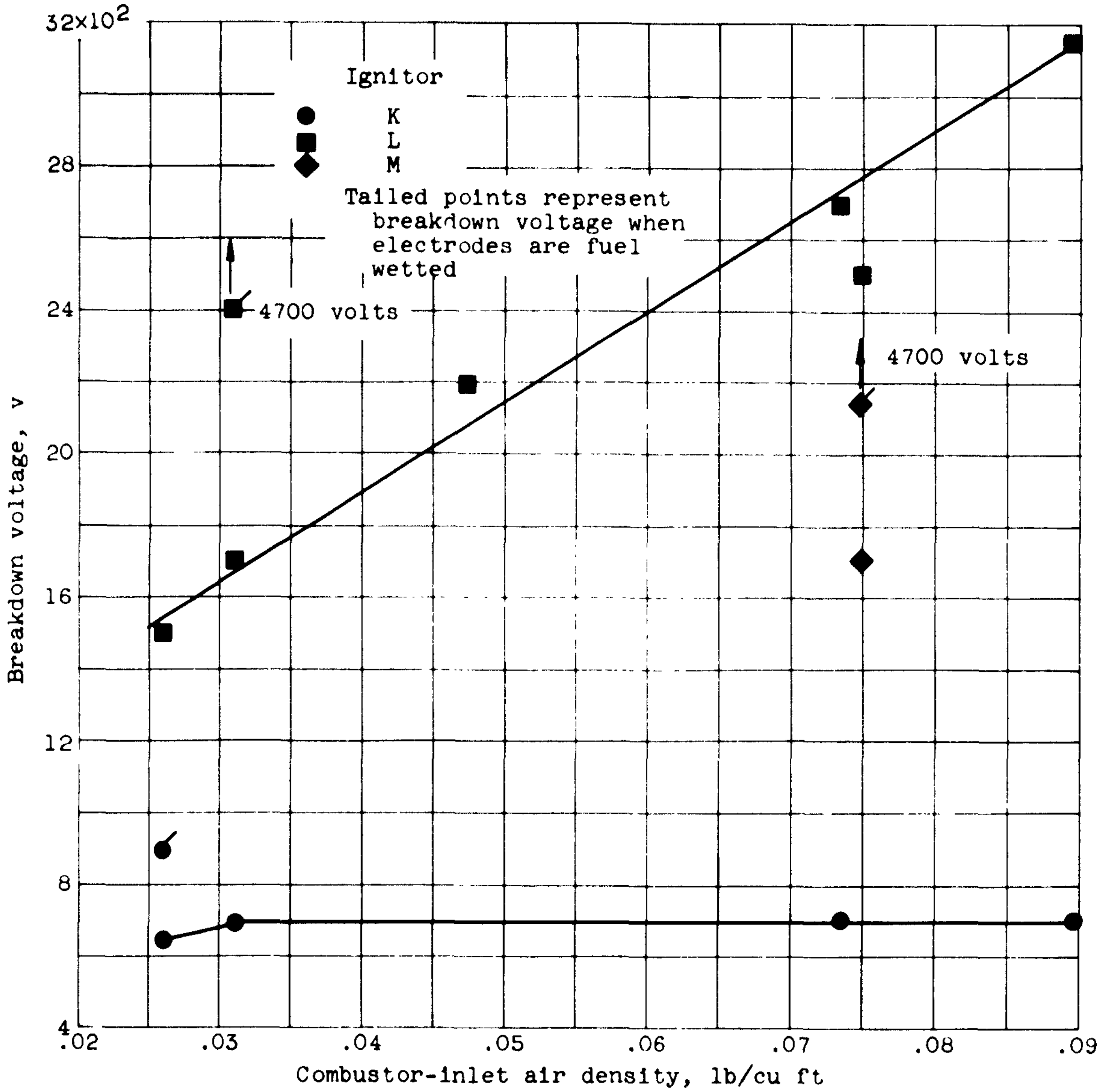

Figure 10. - Effect of combustor-inlet air density on breakdown voltage of several surface-discharge nontriggered-type ignitors. Combustor-inlet air pressure range, 11 to 31.5 inches of mercury absolute; inlet-air temperatures, 10°, 67°, and 100° F.

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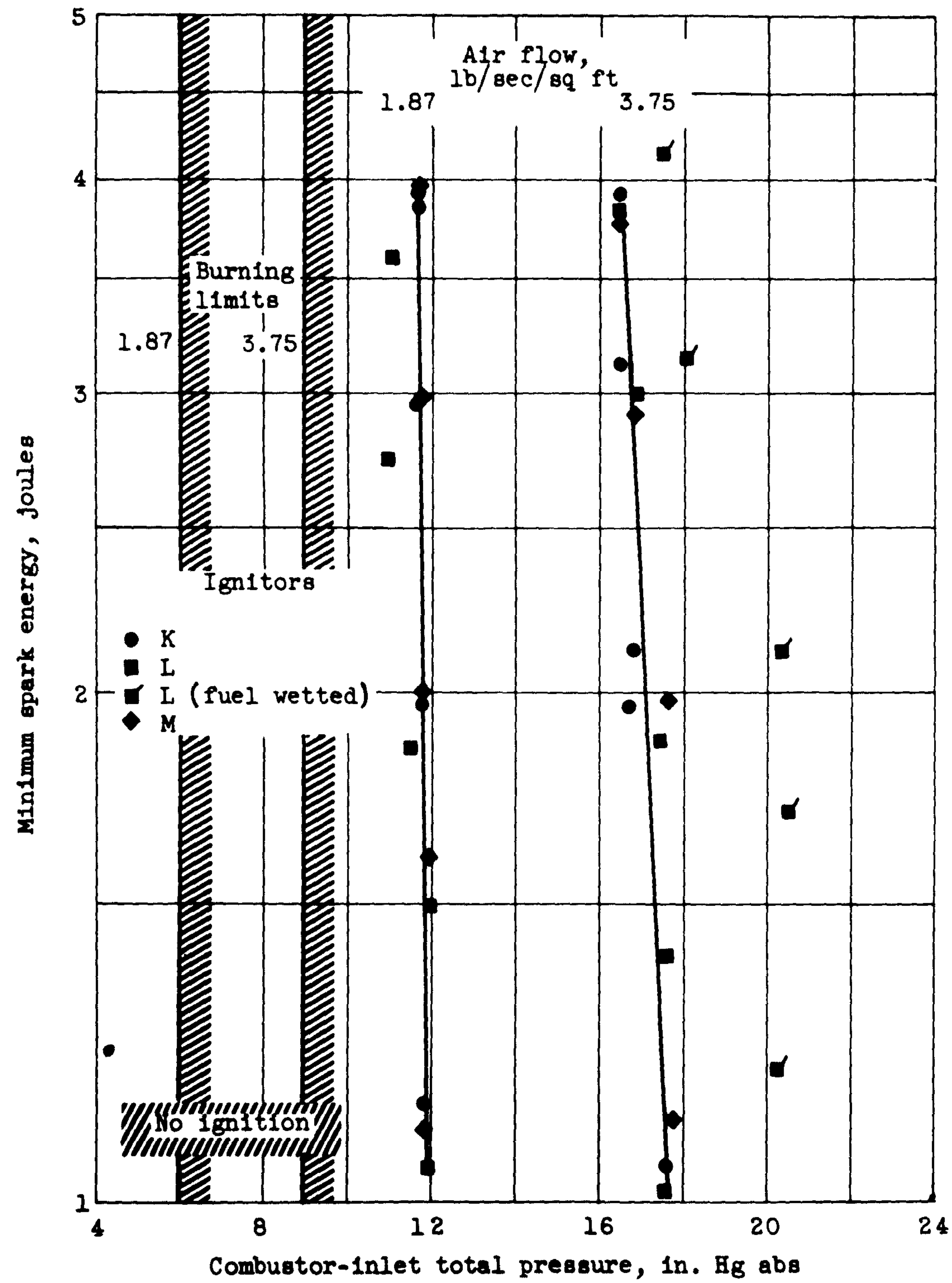

Figure 11. - Ignition limits of several solid-ceramic (nontriggered) surface-discharge ignitors in single tubular combustor. Commercial ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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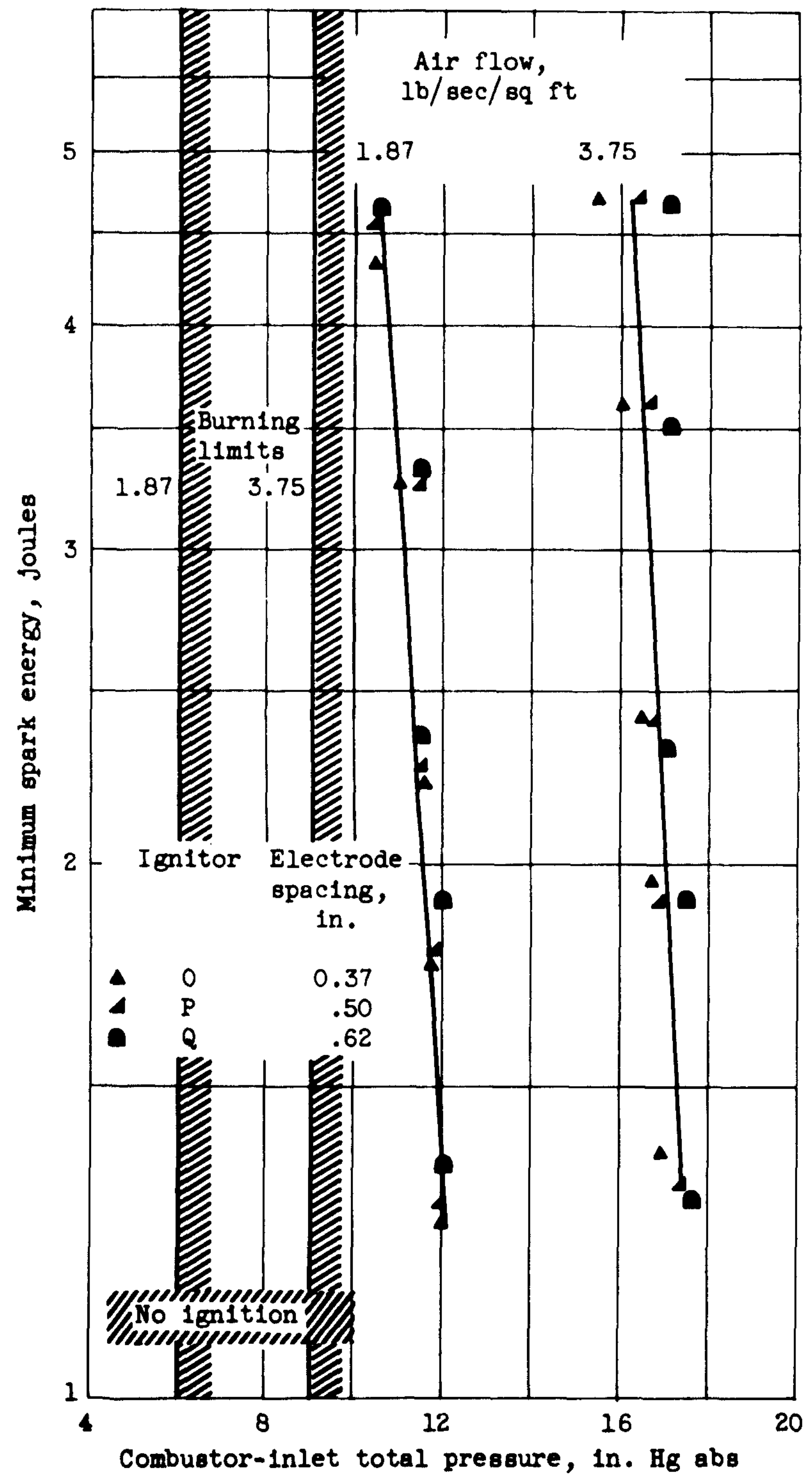

Figure 12. - Effect of electrode spacing on ignition limits of glazed surface-discharge ignitors in single tubular combustor. Commercial ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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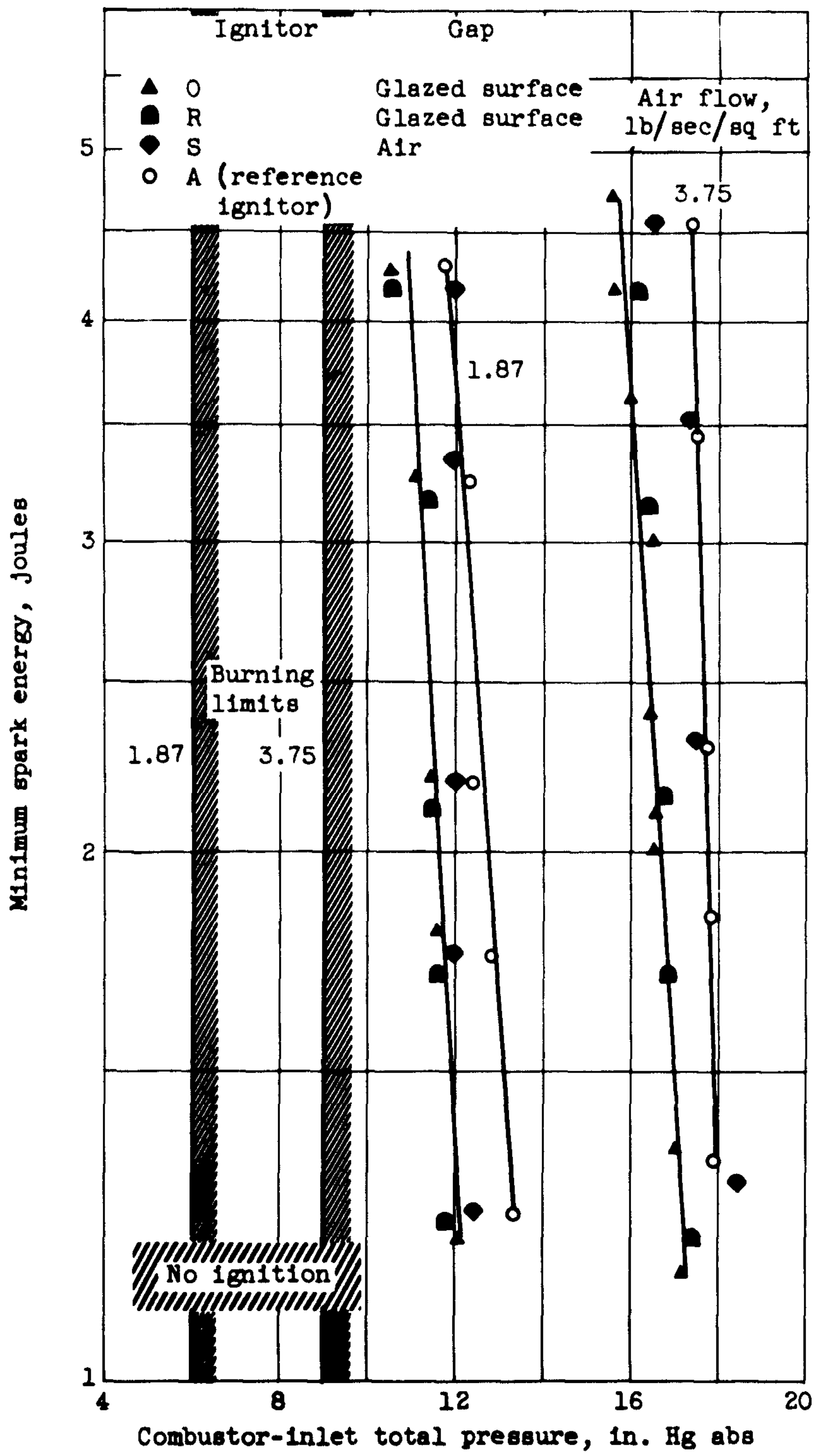

Figure 13. - Comparison of ignition limits of two glazed surface-discharge and two air-gap ignitors in single tubular combustor. Commercial ignition system; fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

CT-6 3049

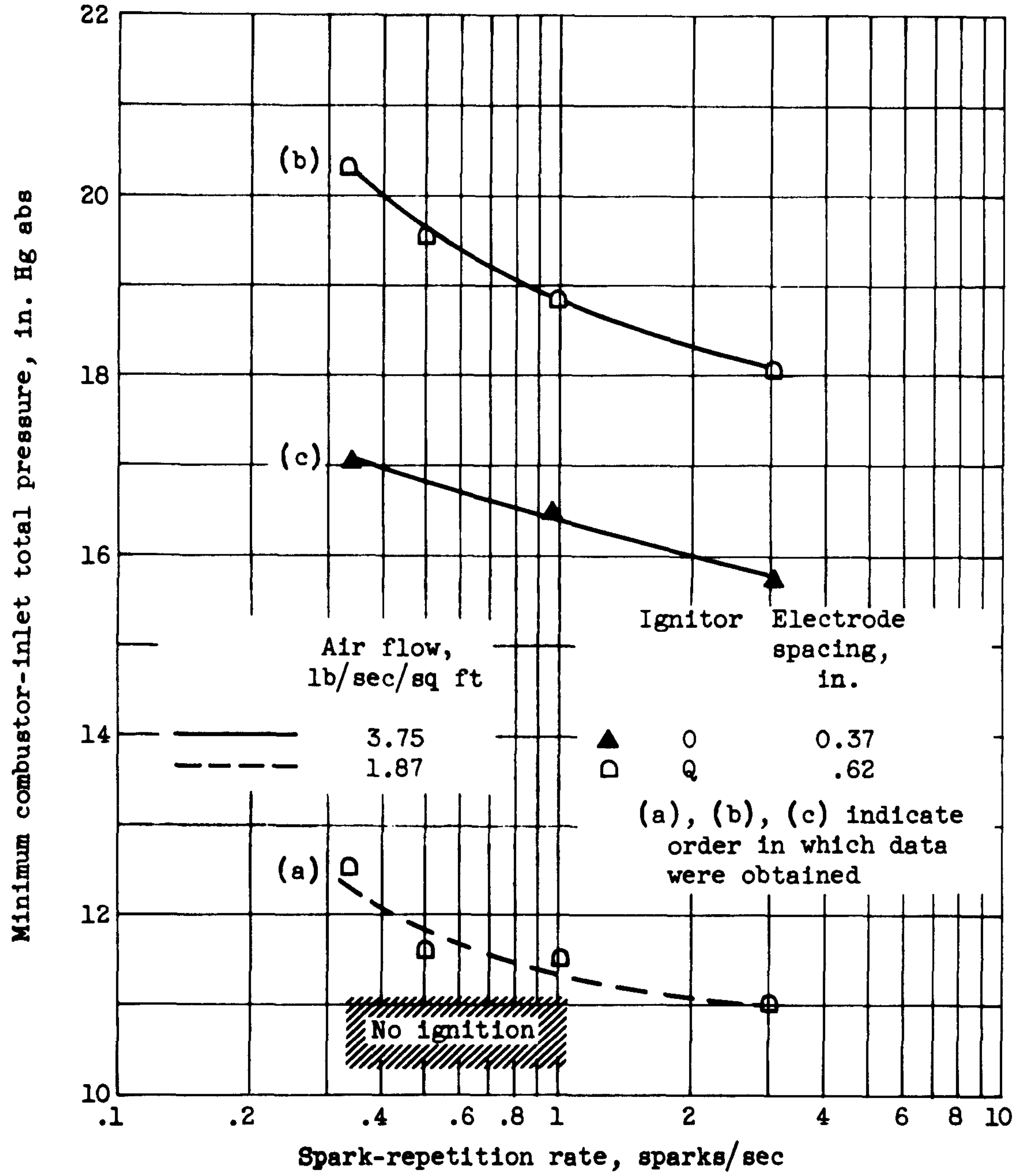

Figure 14. - Effect of spark-repetition rate on ignition limits of single tubular combustor at two air-flow rates. Fuel, NACA 52-288; inlet-air and fuel temperature, 10° F; spark energy, 2.32 joules.

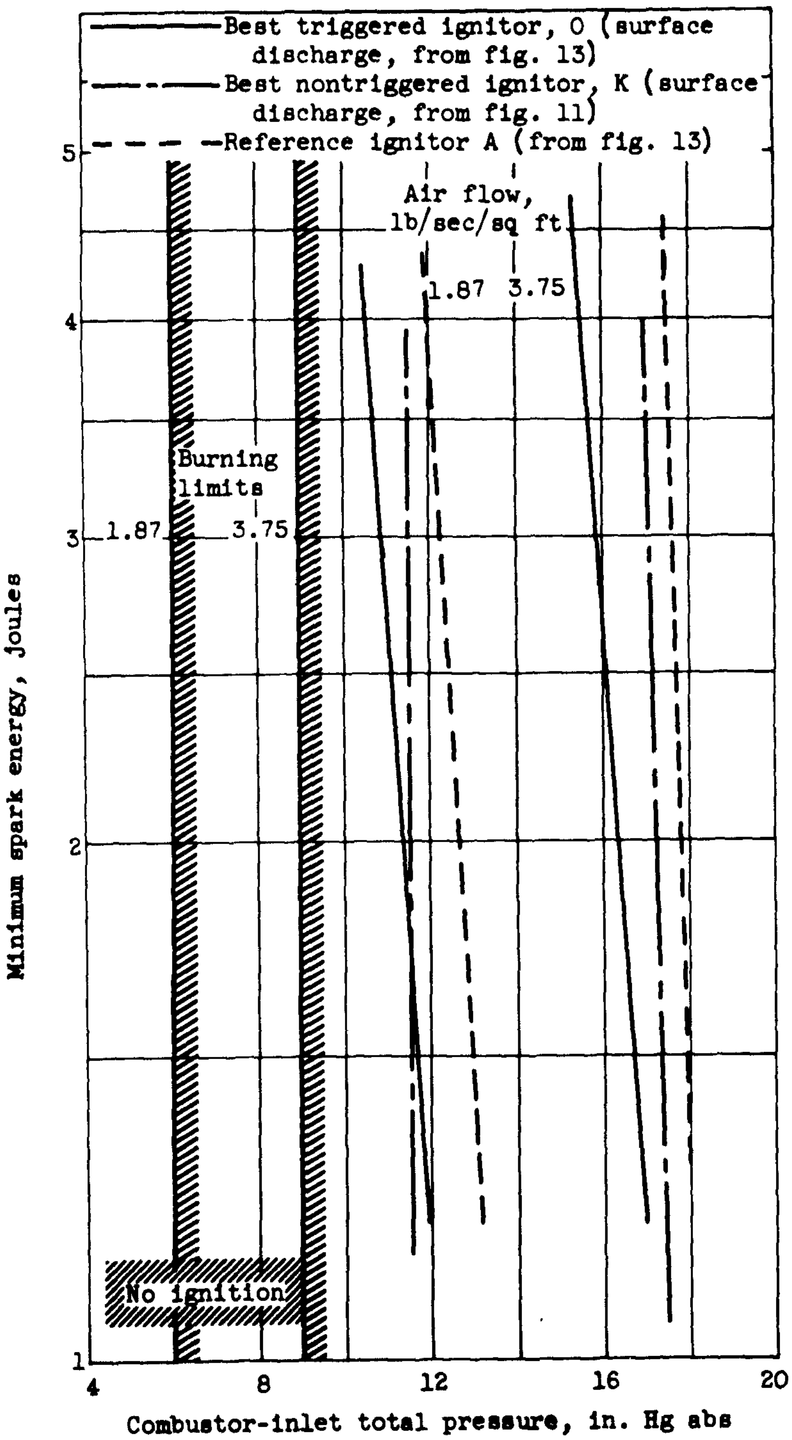

Figure 15. - Comparison of ignition limits of single tubular combustor with the best non-triggered and triggered surface-discharge ignitors and with reference air-gap ignitor A. Commercial ignition system; ignitor installation, figure 4(b); fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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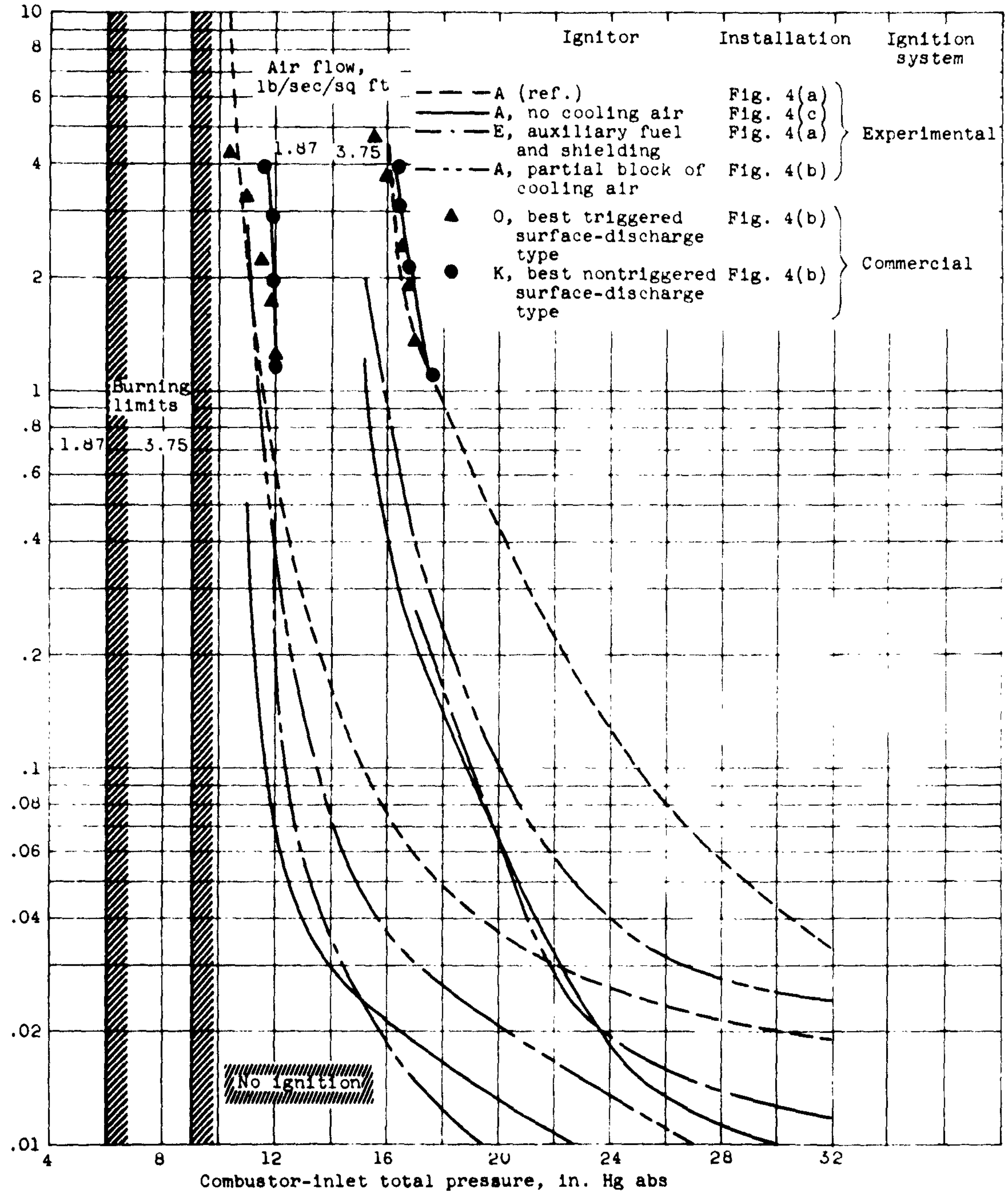

Figure 16. - Comparison of combustor ignition-energy requirements with experimental and commercial ignition systems. Fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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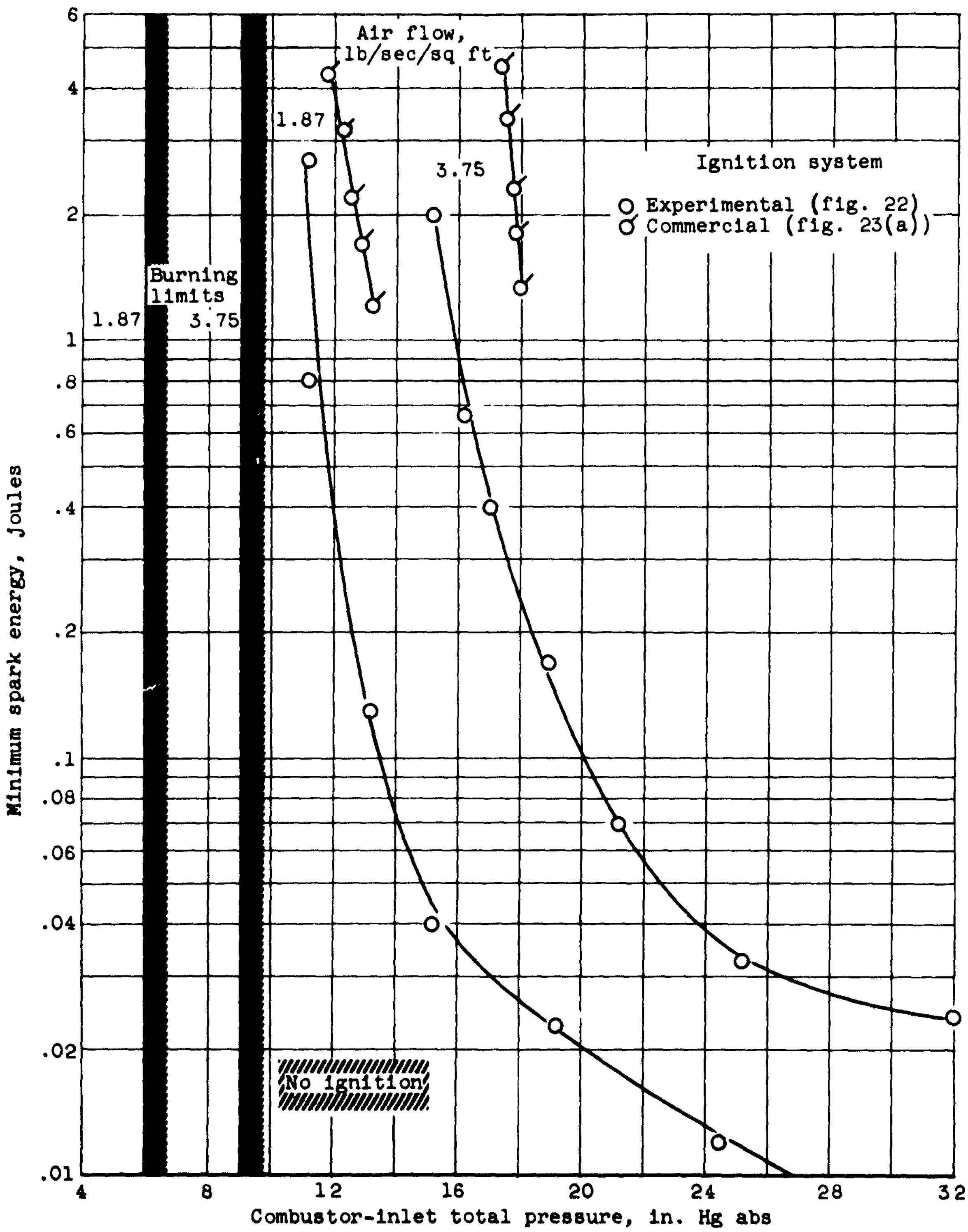

Figure 17. - Comparison of combustor ignition-energy requirements in single tubular combustor with experimental and commercial ignition systems. Ignitor A with partial block of cooling air (fig. 4(b)); fuel, NACA 50-197; inlet-air and fuel temperature, 10° F.

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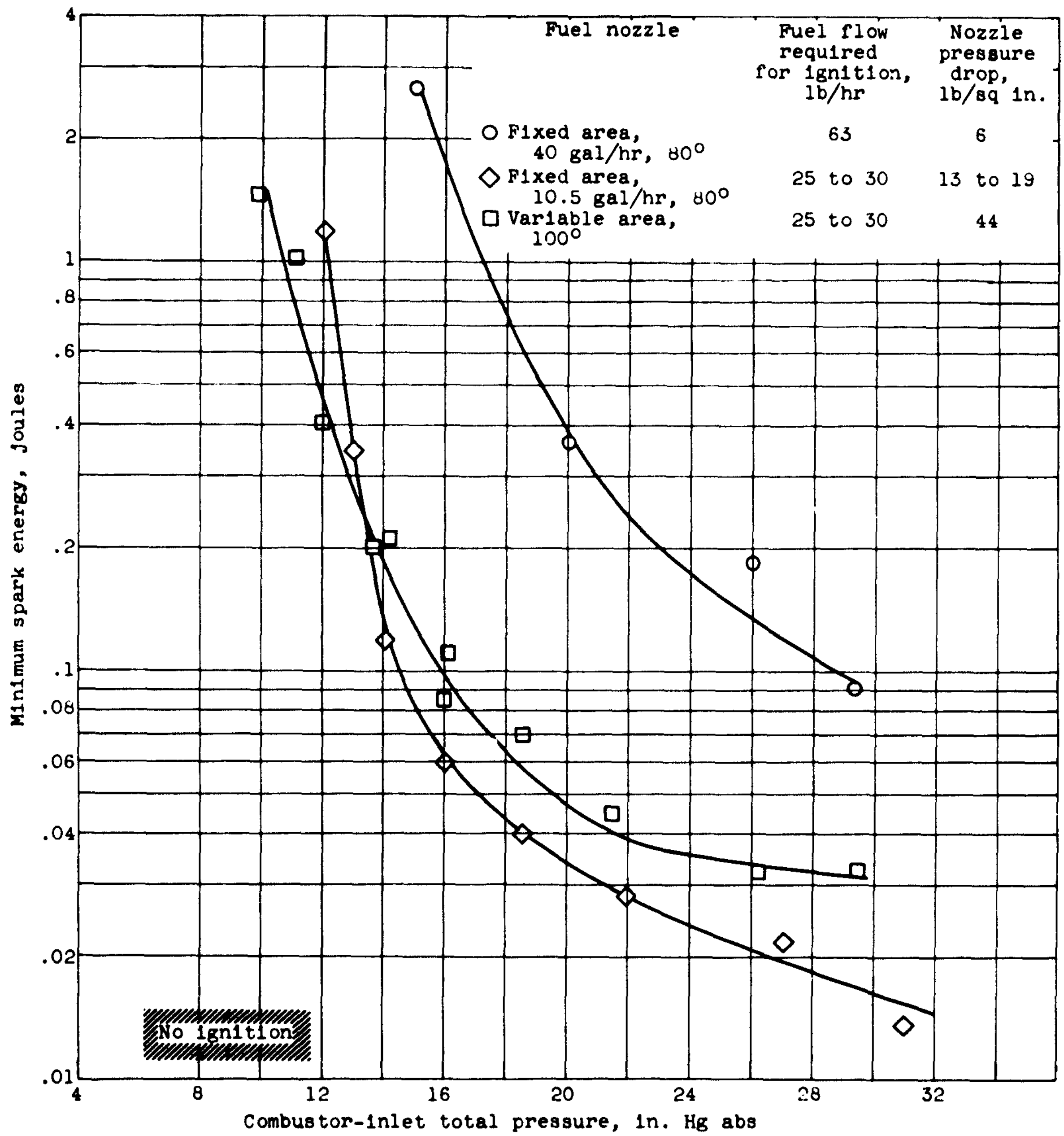

Figure 18. - Effect of fuel-spray nozzle on spark energy required for ignition in single tubular combustor. Experimental ignition system; ignitor A; fuel, NACA 51-192 (ref. 4); air flow, 1.87 pounds per second per square foot; inlet-air and fuel temperature, 10° F.

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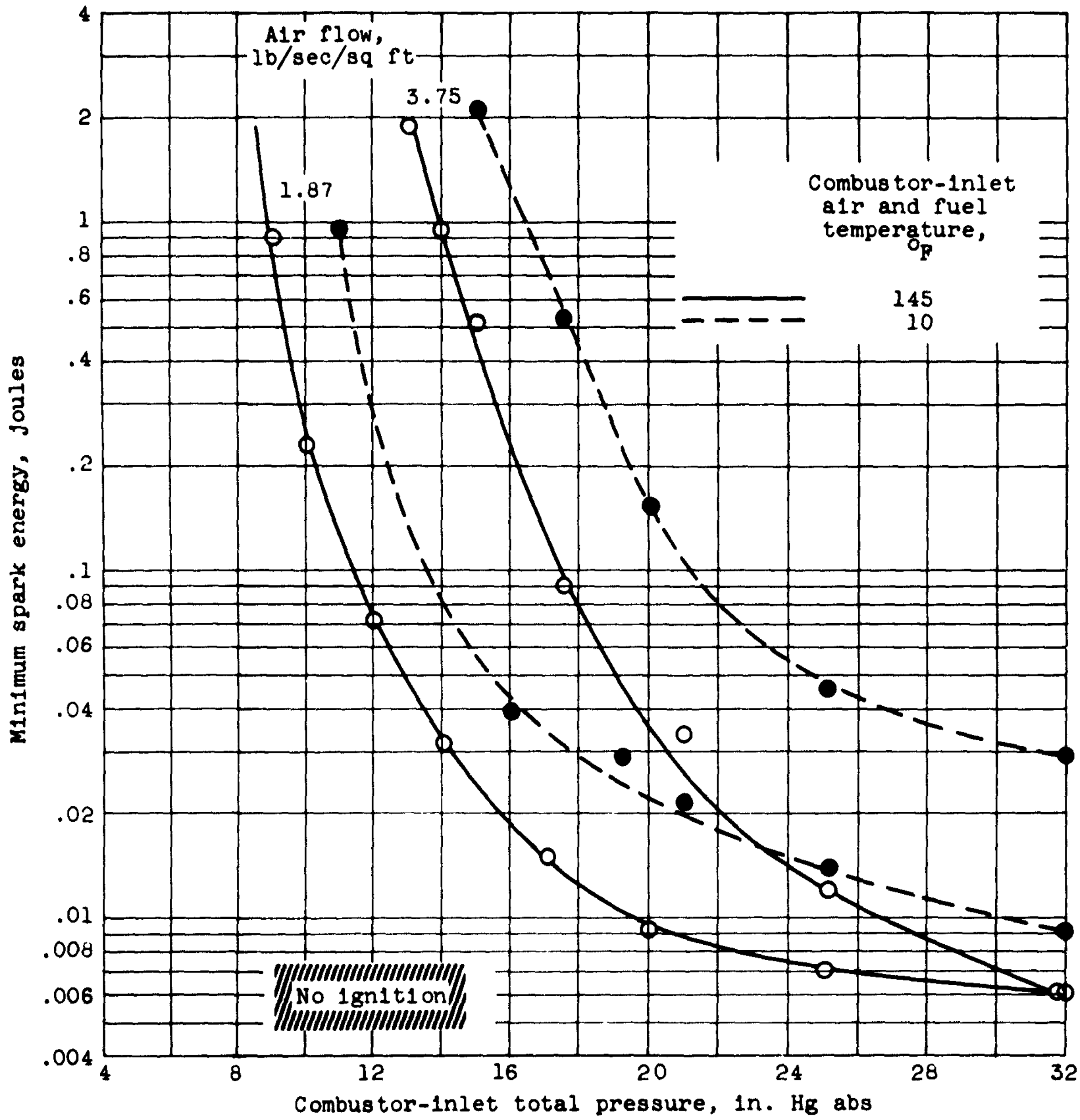

Figure 19. - Effect of inlet-air and fuel temperature on spark energy required for ignition in single tubular combustor. Experimental ignition system; ignitor A, with partial block of cooling air (fig. 4(b)); fuel, NACA 50-197.

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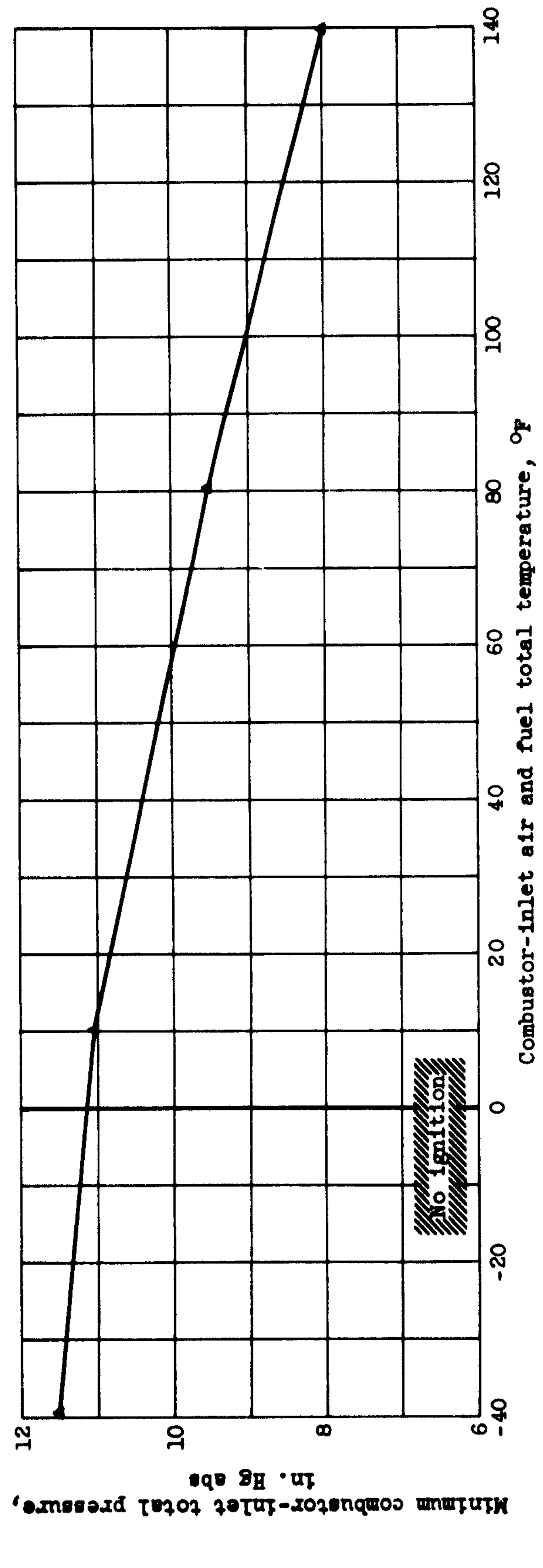

Figure 20. - Effect of inlet-air and fuel temperature on minimum inlet pressure for ignition in single tubular combustor. Triggered commercial ignition system; ignitor O; fuel, NACA 52-288; air flow, 1.87 pounds per second per square foot; spark energy, 2.12 joules.

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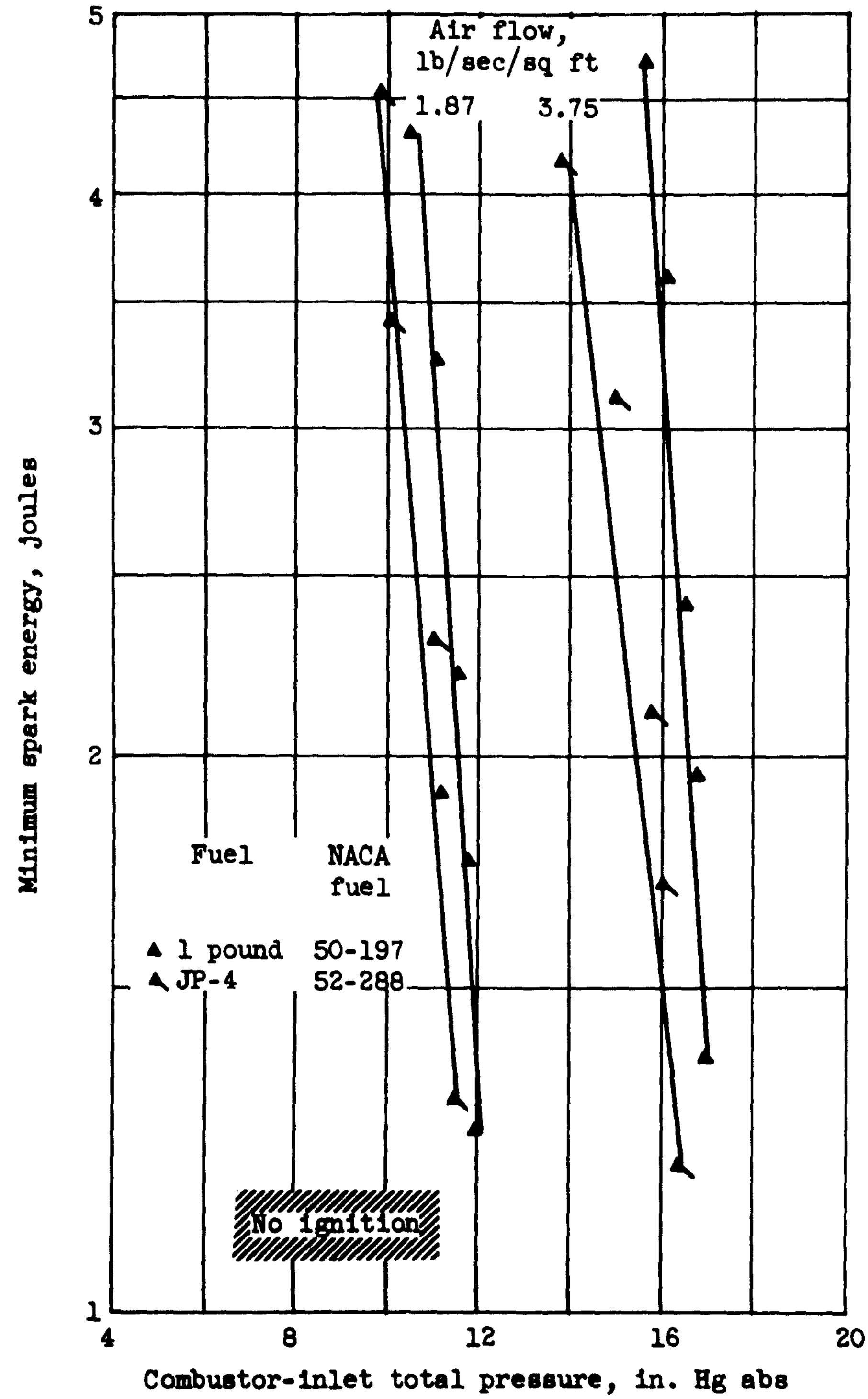

Figure 21. - Effect of fuel volatility on ignition limits obtained in single tubular combustor. Triggered surface-discharge ignitor 0; inlet-air and fuel temperature, 10° F; fuel nozzle, 10.5 gallons per hour, 80° spray-cone angle.

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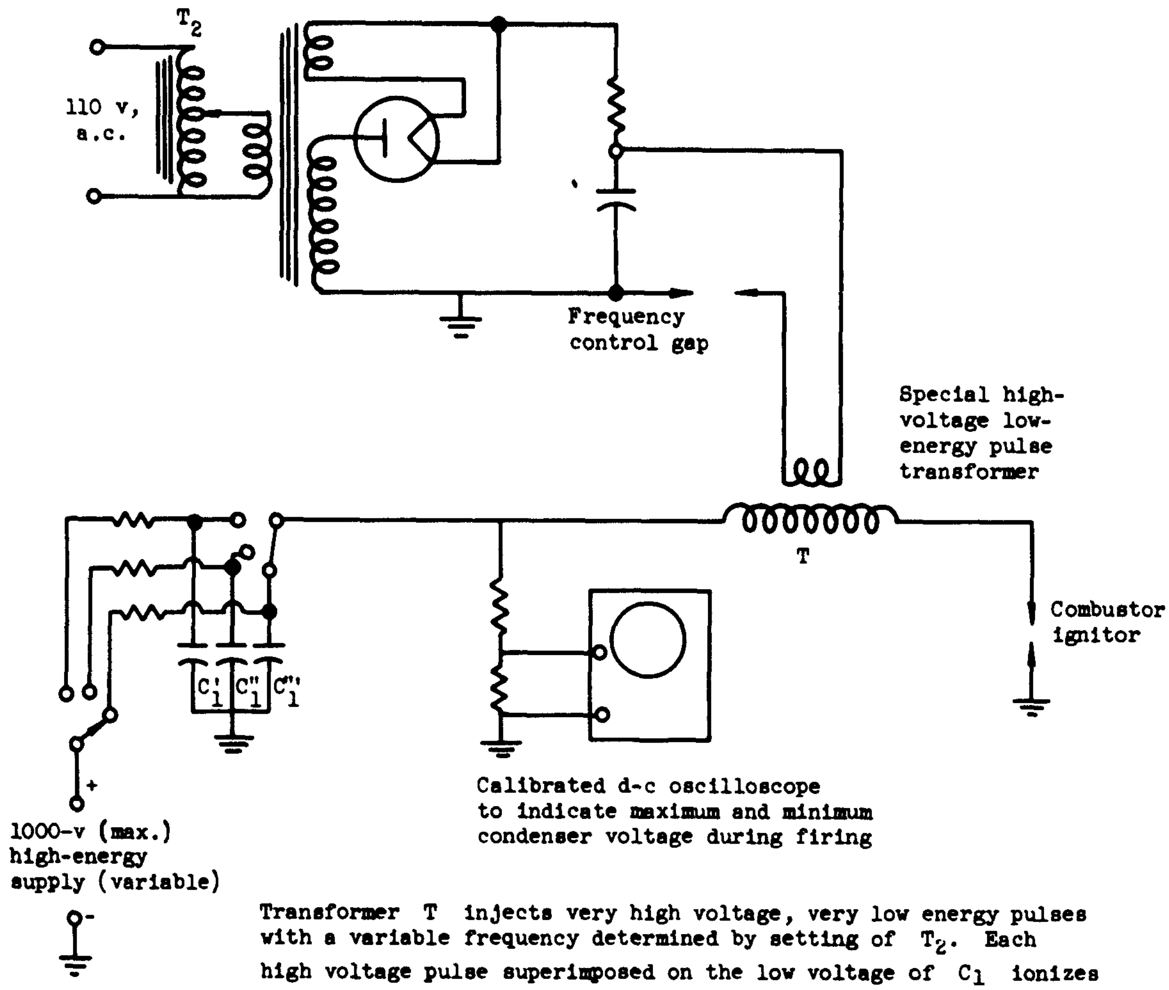
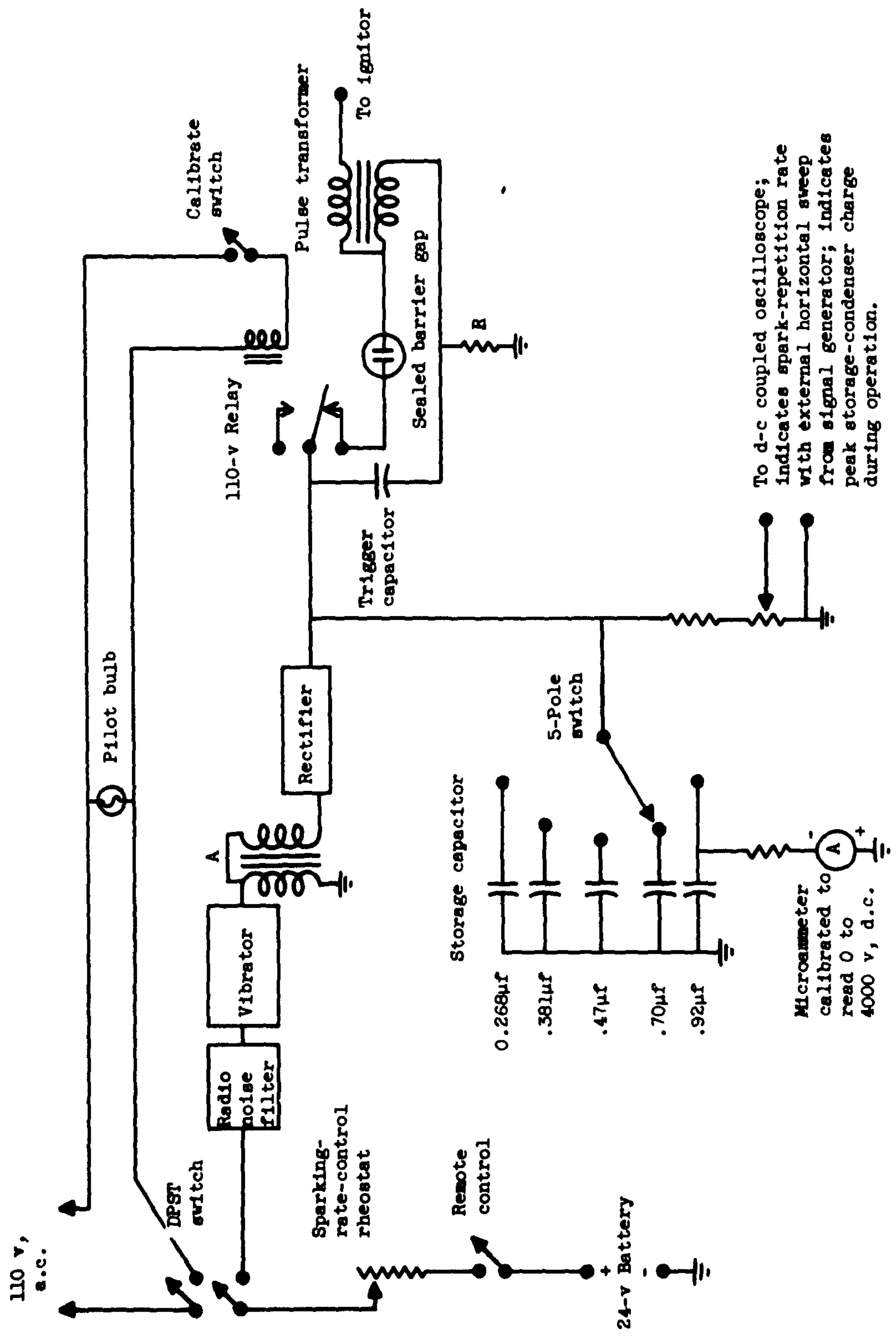


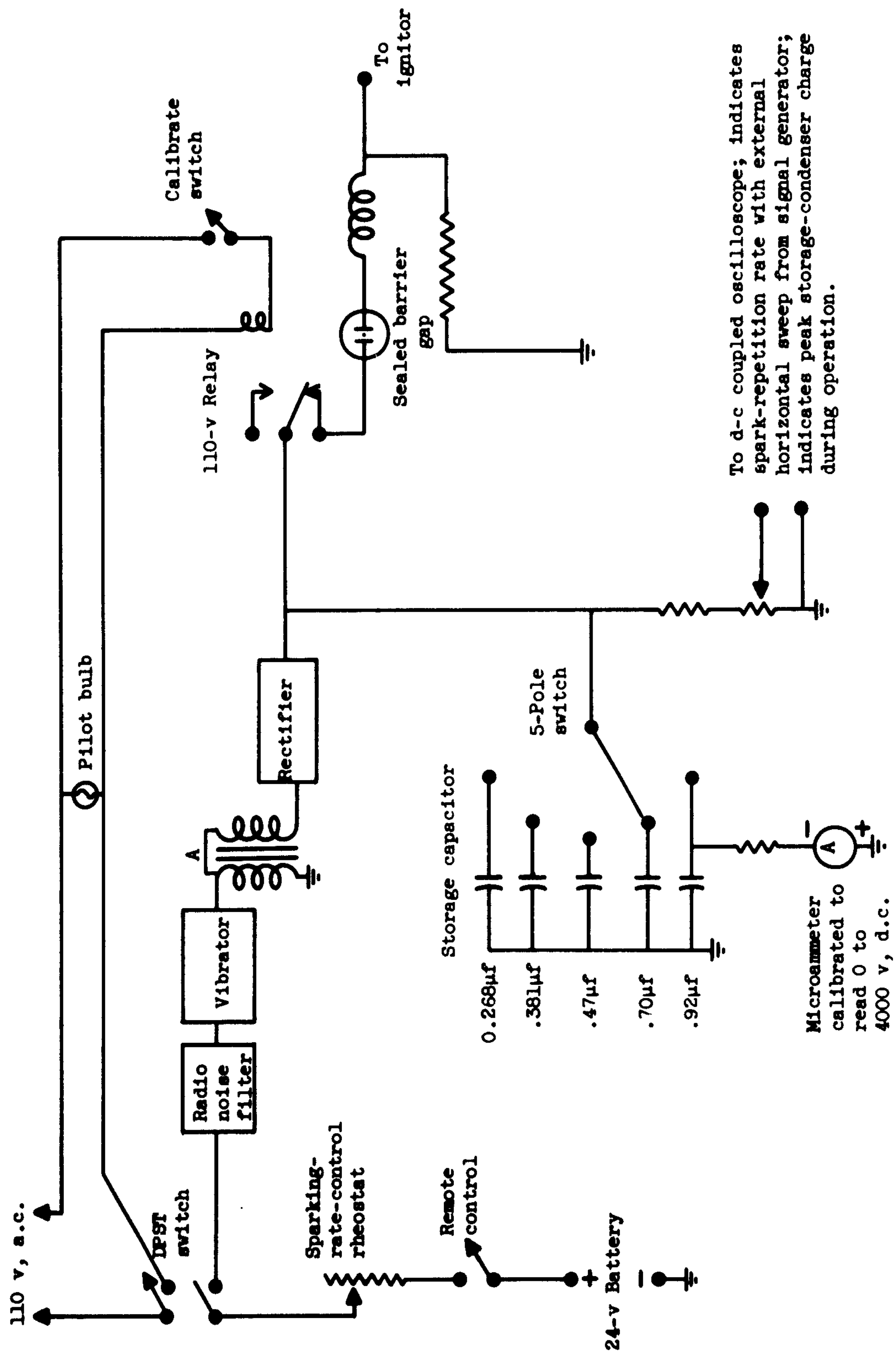
Transformer T injects very high voltage, very low energy pulses with a variable frequency determined by setting of T_2. Each high voltage pulse superimposed on the low voltage of C_1 ionizes the combustor ignitor gap and permits the relatively high energy of C_1 to be discharged through the combustor ignitor. C_1 consists of a bank of condensers, any one of which can be selected to provide a specific known energy per spark.

Figure 22. - Simplified circuit diagram of experimental spark-ignition system (ref. 4).



(a) With 20,000-volt trigger.

Figure 23. - Simplified circuit diagram of commercial ignition system.



(b) Nontriggered.

Figure 23. - Concluded. Simplified circuit diagram of commercial ignition system.

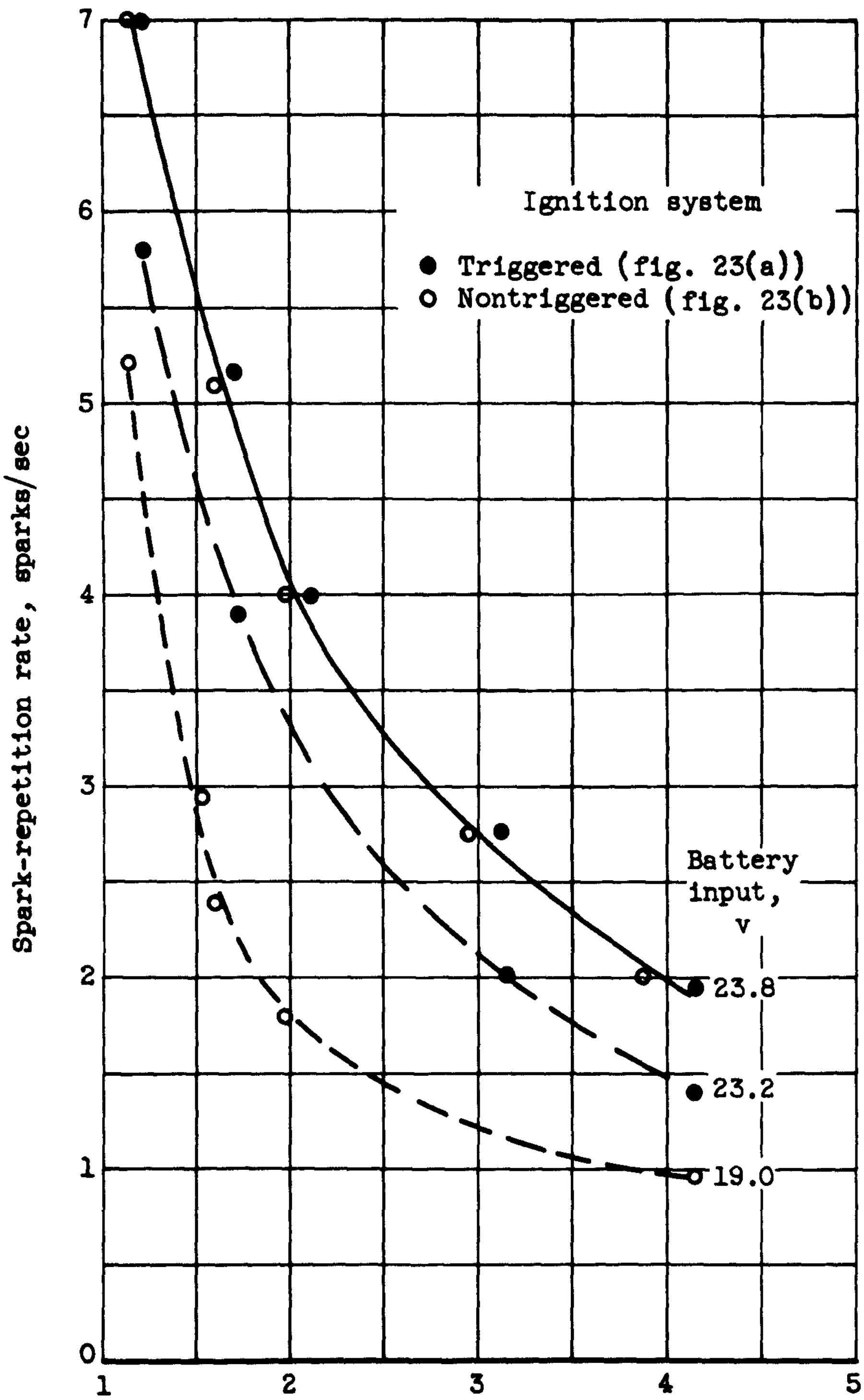


Figure 24. - Variation of spark-repetition rate with spark-energy level and battery-input voltage. Commercial ignition systems.

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A large number of factors which affect the ignition characteristics of turbojet-engine combustors were investigated. The results obtained point to some general design principles for ignitors and ignition systems. Shielding of the ignitor spark gap from high-velocity air flow and improvements in fuel-spray characteristics were effective means of improving ignition characteristics of the combustor; fuel heating and auxiliary fuel feeds at the ignitor gap were ineffective. Little difference in ignition limits was observed with several different designs of surface-discharge ignitors having either solid-ceramic semiconductors or glazed semiconductive coatings. Re-

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